University of Southern Queensland

Faculty of Health, Engineering and Sciences

Analysis of Road Crashes at Roundabouts in Toowoomba

A dissertation submitted by

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in fulfilment of the requirements of

ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Civil)

Submitted October, 2016

ABSTRACT

Every year, road crashes cost Australia an estimated $27 billion in additional to the devastating social impacts these crashes have on the community. Toowoomba's road network has a significant number of roundabouts with approximately one roundabout for every two signalised intersections; with more roundabouts being constructed every year. The aim of this investigation is to evaluate the safety performance at roundabouts in Toowoomba to re-examine the contribution that geometric features of the poorer performing roundabouts have in severity and frequency of road crashes.

A combination of two road safety methodologies were utilised to rank the top 10 worst performing roundabouts in Toowoomba. By combining the two methods more variables were able to be considered in the ranking process; the Critical Crash Rate method considered crashes with respect to traffic volume and the Relative Severity Index method used costs per crash type considering the costs of a crash based on a potential severity. The methods were subsequently combined using scores and weighting factors.

The crash investigations, road safety audits and geometric property investigations conducted at the subject roundabouts identified that the most significant crash contributory factors were high entry speeds and reduced sight distance upon approach to the roundabout. The observed high entry speeds were most commonly associated with entry path radii that were too large as well as inadequate deflection through the roundabout. Insufficient sight distance due to vegetation on the corners of roundabouts was a common issue observed at the subject roundabouts and there were significant numbers of infrangible objects such as electricity/light poles and trees within the clearance zone of the roundabouts.

Remedial measures such as reducing entry path radii, radius of deflection and entry widths to limit entry speed, removal of vegetation on corners of roundabouts to improve sight distance, re-application of faded line marking and symbols to improve driver path through the roundabout and removing/relocating power/light poles located within the clearance zone to reduce the frequency and severity of hit object crashes are recommended in order to improve safety at the subject roundabouts.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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ACKNOWLEDGEMENTS

This research project was carried out under the principle supervision of Dr. Soma Somasundaraswaran. I would like to thank Dr. Soma Somasundaraswaran for his continued guidance and mentorship throughout the project that was invaluable in the preparation of this dissertation. I would like to thank my family, friends and husband for their continued support.

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GLOSSARY OF TERMS

Approach Width the width of the approach carriageway prior to any approach curves

Apron a trafficable raised concrete apron around the central island

Arndt a computer program that identifies the likely safety performance of a new or existing roundabout. It is based on the results of the roundabout study

Circulating Carriageway Width the carriage width measured around the central island

Conflict Points the point at which a road user crossing, merging with, or diverging from a roadway conflicts with another road user using the same roadway.

Crash a set of events that result in injury and/or property damage due to the collision of at least one motorised vehicle with another motorised vehicle, bicyclist, pedestrian or object

Crash Frequency the number of crashes occurring at a particular site, facility or network during a period of one year

Crash Rate number of crashes per percentage population (number of crashes per million entering vehicles)

Crash Severity is a five level categorisation of the severity of a crash, they are fatal, hospitalisation, medical treatment, minor injury and property damage only

DCA Definitions for Coding Accidents

Entry Width the carriage width measured at the entry to the circulating carriageway

Exit Width the carriage width measured at the exit from the circulating carriageway

Remedial Measures changes to roundabout geometry and physical attributes to reduce crash frequency and severity

Road User a vehicle user, cyclist or pedestrian

Sight Distance The distance, measured along a carriageway, over which visibility occurs between a driver and an object (single vehicle sight distance) or between two drivers at specific heights above the carriageway in their lane of travel

Splitter Island the Island placed within a leg of the roundabout to separate the entering and exiting traffic, and designed to deflect entering traffic

Swept Path the area required for a vehicle traversing a roundabout to perform the turning manoeuvre as outlined by the path taken by extremities of the vehicle.

Vehicle transportation modes that utilise road infrastructure (a car, truck, bus, motorbike, cyclist)

1.0. INTRODUCTION

The transport network most commonly used by Australians to travel to work, school, the shops, etc. on a daily basis is the road network. Australia has a very extensive road network system and the car is the most favoured mode of transport available to Australians. According to the 2011 Census data (Australian Bureau of Statistics 2011) the main method of transport to get to work was by car, 65.8% (either as driver or passenger) followed by public transport at 10.4%. With such a high demand on the road network it needs to provide as safe an environment as possible for its users.

One of the key concepts in providing a safe transport system is the ‘Safe System Approach’ outlined in the Austroads guidelines. The Safe System Approach approaches safety with the view that road users are fallible and will make mistakes so the road environment needs to be forgiving for when these mistakes occur (Austroads 2009a). It is not acceptable that the community should be penalised for being human (making mistakes) with death and serious injury which is why the road and vehicles need to be designed to be as safe as possible for when a road crash inevitably occurs (Austroads 2015a). The four key elements of the safe system framework are: safer road user behaviour, safer speeds, safer roads and safer vehicles (Austroads 2015a). Identifying and removing or treating road elements which may be considered to contribute to the severity or the frequency of road crashes is a key component of the safe system approach (Austroads 2015a). This provides for a more forgiving environment when things go wrong.

Every year, road crashes cost Australia an estimated $27 billion as well as the devastating social impacts these crashes have on the community (Australian Government 2016). It is not possible to entirely eliminate the road crashes that occur on Australian roads, however, the road network can be improved to reduce both the frequency and severity of the road crashes to make travelling as safe as possible for the road users.

1.1 Background of Investigation Area – Toowoomba

The study area is the city of Toowoomba located in the Darling Downs, Queensland, Australia, Figure 1.1. Toowoomba is the largest inland city in Queensland with a population of about 150,000 (Australian Bureau of Statistics 2014).

Figure 1.1: Toowoomba Road Network (Google Maps 2016)

Toowoomba's road hierarchy is quite extensive and includes several significant highways, represented by the yellow main roads in Figure 1.1 above, as well as a network of other hierarchy road classifications including: regional arterial roads, subarterial roads, distributer roads, collector roads, local access/access streets, cul-de-sacs and laneways (Toowoomba Regional Council 2016). The relationship between the different road classifications and how they sit in the road hierarchy is represented graphically in Figure 1.2.

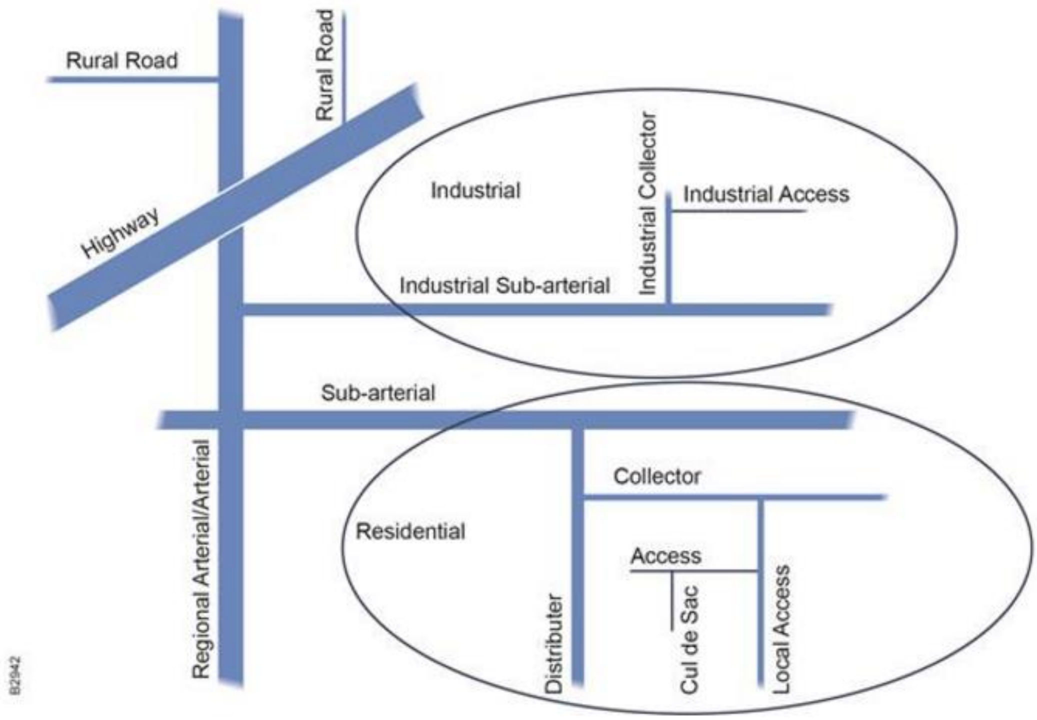


Figure 1.2: Functional Hierarchy of Roads (Toowoomba Regional Council 2016)

The road hierarchy is designed to help traffic flow as efficiently as possible and to ensure the network is accessible and safe. Having a hierarchy of roads encourages only local traffic to frequent local/access streets, which are usually only designed for small volumes of vehicles while through traffic will usually travel on streets at the distributer level or higher where the roads are designed for much larger volumes of traffic.

The two circles in Figure 1.2 above represent the road networks for industrial roads and residential road networks respectively. Throughout Toowoomba there is land use zoning that is designed to keep residential and industrial land uses separate. The road networks are still similar though in that the smaller access roads transport traffic to the collector road for that part of the network, then the collector road facilitates the movement of traffic onto a distributor road that then distributes the traffic to sub-arterial roads that circulate the network.

Toowoomba's climate is usually cooler than other regions in Queensland with a mean daily minimum and maximum temperature of 12.6°C to 23.1°C respectively throughout the year (Australian Bureau of Meteorology 2016). A graph of the average temperatures experienced in the Toowoomba region is shown in Figure 1.3.

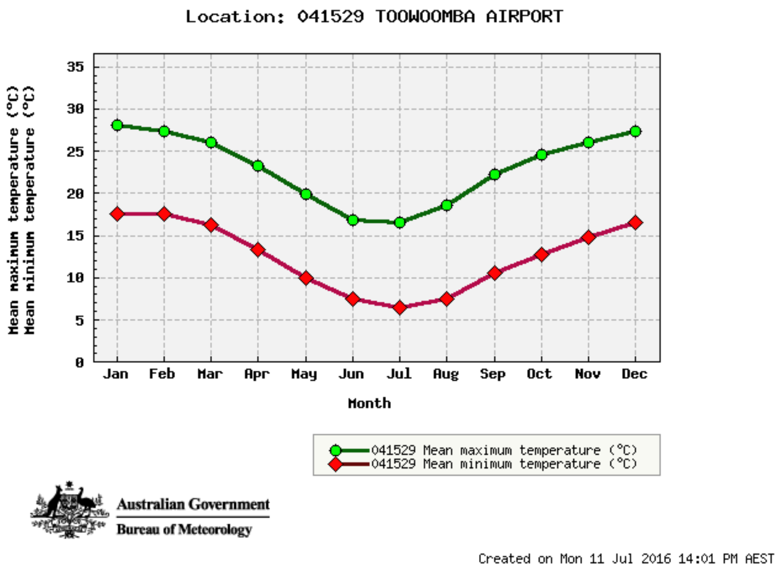


Figure 1.3: Mean minimum and maximum temperatures for Toowoomba region in 2016 (Australian Bureau of Meteorology 2016)

The Toowoomba region usually experiences the highest rainfalls during the summer months with only small amounts of rainfall during winter. This can be seen on the following graph, Figure 1.4.

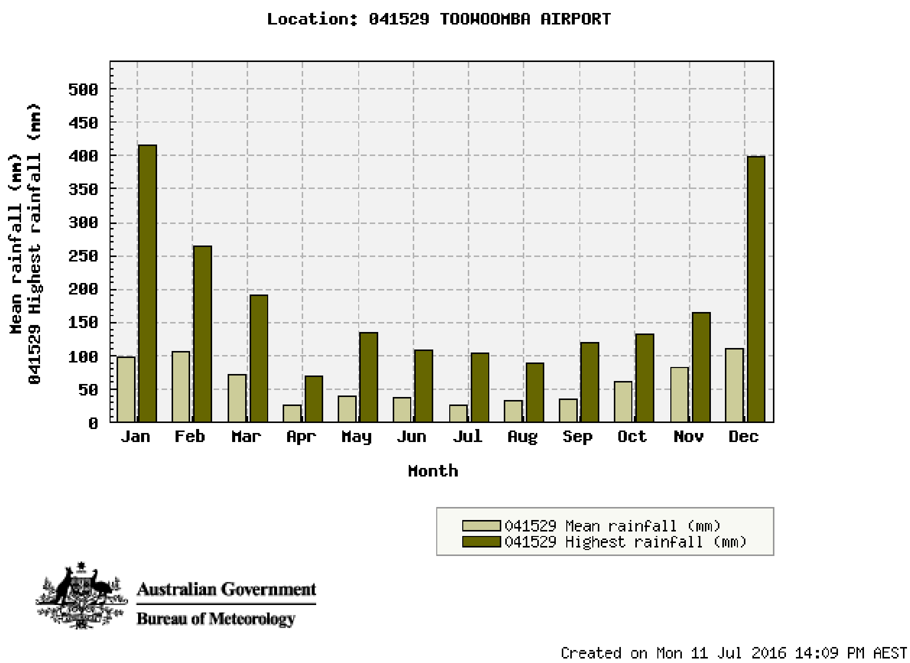


Figure 1.4: Average and Maximum Rainfall for Toowoomba region 1996 to 2016 (Australian Bureau of Meteorology 2016)

It can also be seen in Figure 1.4 that Toowoomba can sometimes experience significantly high rainfall levels represented by the dark green of the highest recorded daily rainfall over the 20 year period. At times when these high rainfalls occur there is a higher risk of crashes due to possible flash flooding, lower visibility and wet roads; requiring the road users to apply a higher level of alertness and caution in these conditions.

Another significant climatic factor that is prevalent in Toowoomba is the fog that is experienced by the region during the cooler months. According to the 'Queensland Past and Present' book published by the Queensland government in 1998, Toowoomba experiences an average of 59.3 days per year of foggy conditions (Qld Government Statistician's Office 1998). Figure 1.5 shows a typical scene on one of Toowoomba's foggy days.

Figure 1.5: Fog in Toowoomba photographed on 10 July 2012 on Margaret Street (*Margaret Street, Toowoomba, fogbound in winter* 2012)

Foggy conditions can significantly limit the road user's visibility and sight distance resulting in a higher risk of crashes. The conditions are usually most prevalent during the night and morning, however, some winter days in Toowoomba can have fog all day long particularly in areas along the range.

1.2 Statement of Problem

The city of Toowoomba has a significant number of roundabouts and more are being constructed each year. Roundabouts are known for being a safer alternative than other intersection types and there are significant benefits in installing roundabouts when they are a suitable option. However, with the number of roundabouts increasing, it is important to ensure that both the existing roundabouts and any new roundabouts being designed and constructed are as safe as possible for the road user. In particular, the geometric properties of roundabouts that can significantly affect roundabout safety need to be considered with care and attention.

1.3 Research Aims and Objectives

1.3.1 Project Aims

The use of roundabouts is widespread in Toowoomba, one of the largest inland regional cities in Australia, yet crashes at these roundabouts contribute a substantial amount to the total crashes. Therefore, the purpose of this study is to analyse the road crash data from roundabouts in Toowoomba with the aim of evaluating the safety performance at each roundabout and to re-examine the geometric features of the poorer performing roundabouts that may be modified to reduce the severity or frequency of road crashes.

1.3.2 Project Objectives

The objectives for this research project are:

1. Quantify (human, economic and social costs), characterise (type of road crash), and interpret crashes at roundabouts to identify significant contributing factors.

2. Gather or develop suitable, scientific based, road safety methodologies for further investigation and analysis of the safety of the roundabouts in Toowoomba.

3. Use several of these methodologies in conjunction with road crash data (Department of Main Roads or other appropriate sources) and traffic volume data (Toowoomba Regional Council) to identify the top 10 roundabouts that have the worst safety performance.

4. Carry out a road safety audit at selected top 10 worst performing roundabouts to collect the geometric and other features that may have contributed to the crashes.

5. Investigate other factors that may have contributed to the road crashes such as, but not limited to; weather conditions, time of day, time of year or type of vehicle involved.

6. Propose appropriate remedial measures to improve the safety of these locations and if they prove significant then make recommendations to Austroads guidelines.

If time permits:

7. Use ARNDT software (or any suitable models) to compare and correlate the geometric features that may be affecting road safety at one or more of the identified roundabouts as a case study.

8. Conduct a regression analysis to produce crash prediction models for the roundabouts in Toowoomba.

2.0. LITERATURE REVIEW

2.1 Introduction

This dissertation will examine the work of researchers in the fields of road safety, road crashes and roundabouts to identify applicable and significant knowledge and information to use for this investigation.

2.1.1 Road Crash Definition

There are several terms used throughout literature when referring to road crashes. These include: ‘collision’, ‘accident’ and ‘crash’. Each of these words generally have the same definition as given in the Highway Safety Manual (AASHTO 2010a) where a set of events result in injury and/or property damage due to the collision of at least one motorised vehicle with another motorised vehicle, bicyclist, pedestrian or an object.

Generally, it is intended in this project that the term ‘crash’ shall be used. There are many variables involved in road crashes, meaning no two crashes are ever quite the same. Road crashes can involve one vehicle or many, can occur anywhere, at any time and can be the result of a large variety of factors or combination of factors such as speed, inattention, drink driving, fatigue, deficiencies in the road and many more (Austroads 2009a).

2.1.2 Crash Frequency and Severity

Crash frequency and crash severity are the two most common ways of analysing road crash data and identifying poor performance of these intersections.

The crash frequency is defined in the Highway Safety Manual (AASHTO 2010a) as the number of crashes occurring at a particular site, facility or network during a period of one year which is simply described by Equation (2.1);

$$Crash\ Frequency = \frac{Number\ of\ Crashes}{Period\ in\ Years} \tag{2.1}$$

The crash severity is separated into five different levels of severity in the crash data obtained from the Department of Transport and Main Roads Queensland. These five levels are:

- Fatal – recorded as a fatality when a person dies within 30 days as a result of injuries sustained in the road traffic crash;

- Hospitalisation – a person transported to hospital as result of injuries from a road crash but does not die from injuries within 30 days;

- Medical Treatment – a person requiring medical treatment (i.e. treatment administered by a medical officer such as a doctor, nurse, paramedic, ambulance officer etc.), but not hospitalised;

- Minor Injury – injury of a minor nature not requiring medical treatment; and

- Property Damage Only – no person was killed or injured in the crash (Queensland Government 2014).

2.1.3 Benefit of Roundabout Vs Other Intersection Type

Roundabouts, when designed well, are regarded as one of the safest forms of intersection control and this has been proved by numerous ‘before and after’ type studies where an intersection has been converted into a roundabout and the crash frequency has reduced (Austroads 2015b). According to Austroads (2015b) the biggest contributing factor to the improvement of road crash frequency at well-designed roundabouts is the reduction in relative speed of vehicles compared to other types of intersections. Thus, designing roundabouts to limit the speed vehicles can travel through them is very important in ensuring the safety performance (Austroads 2015b).

Of the different intersection types, roundabouts are found to be one of the safest types of intersection control. Figure 2.1 illustrates the conflict points at a four leg intersection such as at traffic lights and a four leg roundabout.

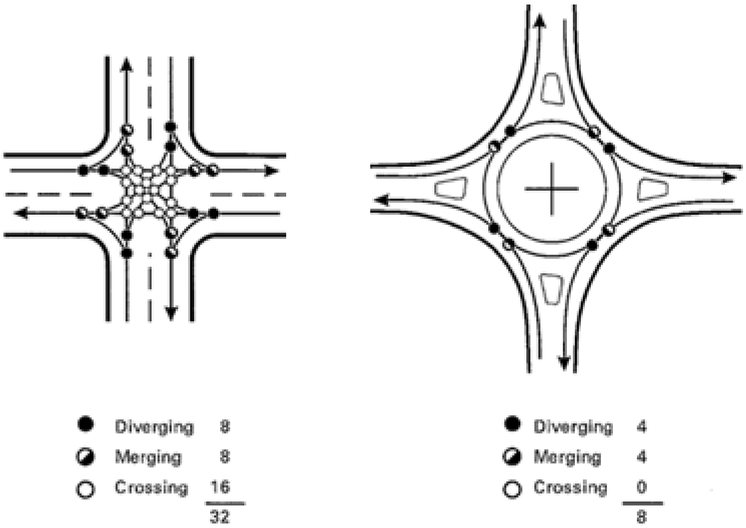


Figure 2.1: Intersection Conflict Points (Federal Highway Administration 2014)

There is a significant reduction in conflict points by having a roundabout because the traffic is travelling in the same direction as they navigate through the circulating road so the only time there are conflict points are as the cars are entering and exiting the roundabout. One of the biggest advantages of roundabouts is their ability to slow the traffic before they enter the roundabout through the use of deflection angles and geometry which can significantly reduce the severity of any crashes that may happen (Federal Highway Administration 2014).

2.1.4 Road Hierarchy

The Toowoomba Regional Council's Planning Scheme has a defined road hierarchy for the road network in the Toowoomba region as well as a map that displays the hierarchy of roads, Figure 2.2.

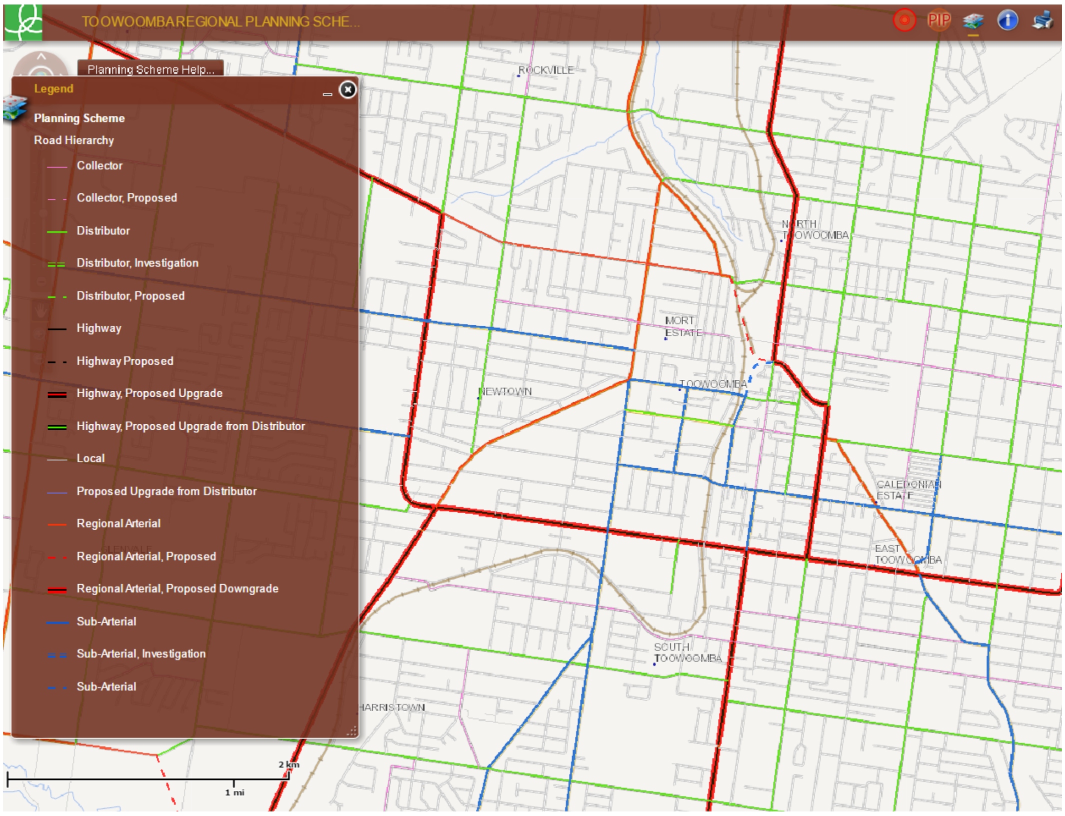


Figure 2.2: Toowoomba Regional Council Planning Scheme Road Hierarchy Map (Toowoomba Regional Council 2016)

The definitions given in the planning scheme of the types of roads in the hierarchy are discussed in the following sections.

Highways are national and state roads that have a desirable capacity of four to eight lanes and 45,500 to 91,000 vehicles per day (VPD) and connect cities, major centres or state-significant activities (Toowoomba Regional Council 2016). The Department of Transport and Main Roads (DTMR) are responsible for these roads including the speed environment, design and maintenance (Toowoomba Regional Council 2016). Any intersections with a highway are designed to accommodate the turning movements of a Class 11 Type 1 road train (Toowoomba Regional Council 2016).

Regional arterial roads link regional activities and centres and circulate traffic through the council region with a desirable capacity of four to six lanes and 33,150 to 49,920 VPD (Toowoomba Regional Council 2016). The speed limit environment is usually 60-80km/h in urban environments, and similar to highways, intersections with regional arterial roads are designed to cater for the turning movements of vehicles up to a Class 11 Type 1 road train (Toowoomba Regional Council 2016). On street parking is not permitted but indented bus stops are provided in the urban area (Toowoomba Regional Council 2016).

Subarterial roads circulate traffic within the CBD as well as other regionally significant activity areas (e.g. the airport, the Toowoomba Base Hospital and the University of Southern Queensland) (Toowoomba Regional Council 2016). The speed environment is 60-80km/h in the urban area and 60km/h in the inner urban area, indented bus lanes are provided and on street parking is limited to only short term stays and service vehicles (Toowoomba Regional Council 2016). Intersections are usually signalised or a roundabout in the urban area and are usually spaced at least 0.5 km apart (Toowoomba Regional Council 2016). Intersections on subarterial roads are also designed to accommodate the turning movements of a Class 11 Type 1 road train (Toowoomba Regional Council 2016).

Distributer roads allow the movement of traffic through districts with a speed environment of 60km/h in the urban environment and 50-60km/h in the inner urban area (Toowoomba Regional Council 2016). On street parking is usually only limited to short term and service vehicles and indented bus lanes are provided in urban areas (Toowoomba Regional Council 2016). Intersections with distributer roads are usually T intersections or roundabouts and are usually spaced at least 200m apart with the ability to accommodate the turning movements of vehicles up to a Class 10 B-double truck (Toowoomba Regional Council 2016).

Collector roads allow the movement of local traffic to the distributer road network, usually providing for up to 300 dwellings or 30ha of industrial land (Toowoomba Regional Council 2016). The speed environment is 40-60km/h in the urban area and 10-50km/h in the inner urban area with on street parking usually limited to service vehicles and short term stays (Toowoomba Regional Council 2016). Intersections are usually spaced at least 100m apart and are usually a priority T configuration or roundabout designed to accommodate the turning movements of a vehicle up to a Class 9 semitrailer in the urban area and Class 11 Type 1 road train in the industrial area (Toowoomba Regional Council 2016).

Local access/access streets usually only provide access for up to 175 dwellings or 8ha of industrial land with a speed environment of 40-50km/h in the urban environment and 10-50km/h in the inner urban area with on street parking generally permitted (Toowoomba Regional Council 2016). Intersections are usually a priority T configuration or sometimes a roundabout, typically spaced at least 100m apart and are usually designed to accommodate the turning movements of vehicles up to a Class 6 service vehicle in urban areas and a Class 11 Type 1 road train in industrial areas (Toowoomba Regional Council 2016).

Cul-de-sacs and laneways are present in the Toowoomba road network; however, they do not form part of a study of roundabouts as there is not enough traffic volume to warrant an intersection control such as a roundabout.

Some examples of roads that fit into each road classification of the road hierarchy within the Toowoomba region include:

- Highway – Warrego Highway, New England Highway and Gore Highway (Significant sections of these highways that pass through Toowoomba are proposed to be downgraded to regional arterial roads following the construction of the Toowoomba Second Range Crossing (TSRC));
- Regional arterial roads – Anzac Avenue, West Street and Mort Street;
- Subarterial roads – Herries Street, MacKenzie Street and Hursley Road;
- Distributer roads – McDougall Street, Alderley Street and North Street; and
- Collector roads – Campbell Street, Lindsay Street and Long Street.

2.2 Components of Traffic System

The Traffic System can be categorised into four main components: travel Speed, the road user, the road environment and the vehicle (Austroads 2009a).

2.2.1 Travel Speed

Travel speed can have a significant impact on the occurrence of crashes as well as the severity. In lower speed environments the chance of a crash is reduced because the road user is less likely to lose control and there is more time for the road user to make decisions, take evasive action and stop in a shorter distance (Austroads 2009a). Similarly, there is less crash impact energy involved in low speed environments which can reduce the severity of injuries as a result of a crash (Austroads 2009a).

A fundamental element of the safe system approach is managing the inter-relationship between travel speed, road infrastructure design and vehicle safety. There are two different principles that can be used to approach travel speed as a safety factor. These are ‘separation’ or ‘integration’ and were derived from Swedish Vision Zero philosophy (Austroads 2009a). An example of how these two approaches work differently is; in areas of lots of pedestrians, the pedestrians should not be exposed to vehicle speeds any higher than 40km/h. This can be achieved either by separating the pedestrians from the vehicles (separation) or by reducing the travel speed to 40km/h (integration) (Austroads 2009a).

One of the most common approaches of reducing travel speed is the introduction of traffic calming devices or signage.

Some facts from the Australian Transport Council (2006) regarding travel speed are:

- Speeds >5km/h above average in urban areas and >10km/h above average in rural areas doubles the risk of injury in a crash;
- Whereas, reductions in as little as 1-2% of average speed results in substantially greater reductions in fatalities and serious injuries; and
- The chances of surviving a crash decrease significantly above certain speeds depending on the road user type involved and the type of crash.

2.2.2 The Road User

One of the most basic tasks of road design is to design a safe road where road users (whether a driver, pedestrian or cyclist) can make good decisions and intervene effectively in traffic systems (Austroads 2009a). It is important during design to consider and understand human performance, capabilities and behaviours.

The road user is required to process a significant amount of information during the driving task to make safe and efficient decisions. The safe operation of the road system is dependent on the road user making these decisions correctly. However, when the road user makes mistakes, the road environment needs to be forgiving to minimise the impacts of the incorrect decision (Austroads 2009a).

There are three essential driving tasks:

- navigation – trip navigation and route following;
- guidance – following road and maintaining safe path in response to traffic conditions; and
- control – steering and speed control (Austroads 2009a).

These driving tasks require the driver to:

- receive inputs (mostly visual);

- process inputs;
- make predictions about alternative actions;
- decide which are the most appropriate alternative actions;
- execute actions; and
- observe their effects through reception and processing of new information (Austroads 2009a).

It is important during the design of roads and intersections to consider how the road user will process the information provided to them to make the correct decisions. The road user gathers information from the layout of the road, road features and other road users and the rate at which the road user needs to receive and process information must be steady to allow road users to remain in control of the vehicle (Austroads 2009a). If the rate at which decisions need to be made (input – demand) exceeds the driver's capability (output – performance) the resulting stress can cause the road user to make mistakes in one or more of the three driver tasks: navigation, guidance or control, Figure 2.3 (Austroads 2009a).

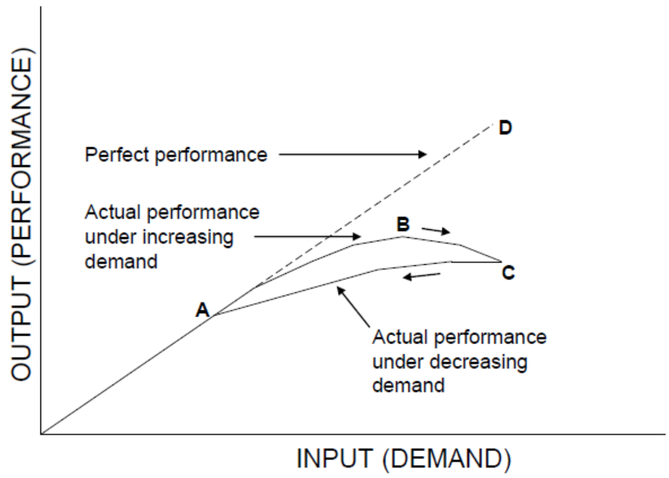


Figure 2.3: Information Processing Model (Austroads 2009a).

When the demand on the road user is low, the road user's performance matches the demand and all inputs can be processed correctly leading to appropriate decisions. However, the performance of the road user, Figure 2.3, reaches a point (A) where the road user can no longer perform at the same rate as is demanded because there is too much information for the road user to process. If the demand increases further, there will be a peak point where the road user reaches their maximum performance. This state of maximum performance cannot be sustained so the more the demand increases past this point the lower the performance of the road user will become due to overload of information. If the road user is significantly overloaded there can be residual effects on the performance of the driver even when the demand is reduced (C to A) (Austroads 2009a). This effect is known as the hysteresis effect where the overloaded driver does not return to the same level of performance when the demand is removed (Austroads 2009a). One of the key design features to consider in relation to this is to avoid placing pedestrian crossings, bus stops etc. immediately downstream of a road feature requiring intense driver attention (Austroads 2009a).

Road user's prior experience develops over time into useful experiences that allows for anticipation and forward planning during the driving task (Austroads 2009a). There are three types of expectancy as described by (Näätänen & Summala 1976):

- Continuation expectancy – events of immediate past will continue (e.g. straight road will continue straight or car in front will continue at past speed);
- Event expectancy – events which haven not happened will not happen (e.g. train will not come through this level crossing because road user hasn't seen one here yet); and
- Temporal expectancy – events are cyclic (e.g. traffic signals), the longer a given state occurs, the greater likelihood change will occur (e.g. drivers may speed up to avoid an anticipated red signal).

When information is received by the road user in the expected form, and the events occur the way they are expected, the road user's performance is likely to be error free (Austroads 2009a). Road crashes are much more likely to occur when the information received does not match the expectations of the road user (Austroads 2009a).

The reaction time for the road user to physically react to the occurrence or appearance of a 'signal' (usually visual) can be significantly reduced as a result of expectancies because the road user can respond through familiarity and habit (Austroads 2009a). There are a wide range of individual variables which can also affect the reaction time of individual road users such as experience, skill, degree of alertness, motivation, risk-taking behaviour, blood alcohol level etc. (Austroads 2009a). Another evident factor that can significantly reduce the reaction time for a road user is the travel speed because as the speed increases the vehicle will travel further before the road user can react (Austroads 2009a).

Memory has a significant role in the driving task as the mind needs to process all of the information and keep the important information. According to Wickens (1984) human memory may be considered as having three stages:

1. Sensory Memory – momentary and sensitive to incoming stimuli. Most of the incoming stimuli will be discarded if it doesn't require processing and rapidly replaced with new stimuli;

2. Short term memory (working memory) – temporary storage of information that needs to be processed. The information needs to be actively reinforced within about 30 second before it is lost; and

3. Long term memory – once committed to long term memory the information can be recalled at a later date (Austroads 2009a).

During the driving task, most of the incoming stimuli such as signs, signals, pavement marking, other vehicles, pedestrians etc. will make it to short term memory for routine processing before being replaced with new information (Austroads 2009a).

The visual characteristics of the road environment are the main source of information for the road user so are an important factor to consider. For the road user there are several factors that can influence how well they can receive the information, one of the most significant is the visual field of the road user. In order for the road user to see a signal, sign, road marking etc. it needs to be within their visual field (Austroads 2009a).

2.2.3 The Road Environment

The road environment needs to assist the road user by providing a safe, forgiving and informative environment that will recognise the limitations of human decision making (Austroads 2009a). As outlined in the Austroads manual, Treatment of Crash Locations, a safe road environment should have the following characteristics;

- Provide no surprises in road design or traffic control – design matches road user expectations;

- Provide controlled release or relevant information – design matches information processing abilities of the road user; and

  Provides repeated information, if required to emphasise danger – ensure design matches expectation (Austroads 2009a).

The road environment should provide warning of any unusual road features, guide and inform the driver of the conditions ahead and control the driver's passage through conflict points in an intersection (Austroads 2009b).

The Department of Transport and Main Roads discusses the requirements of clear zones at roundabouts in their Road Landscape Manual.

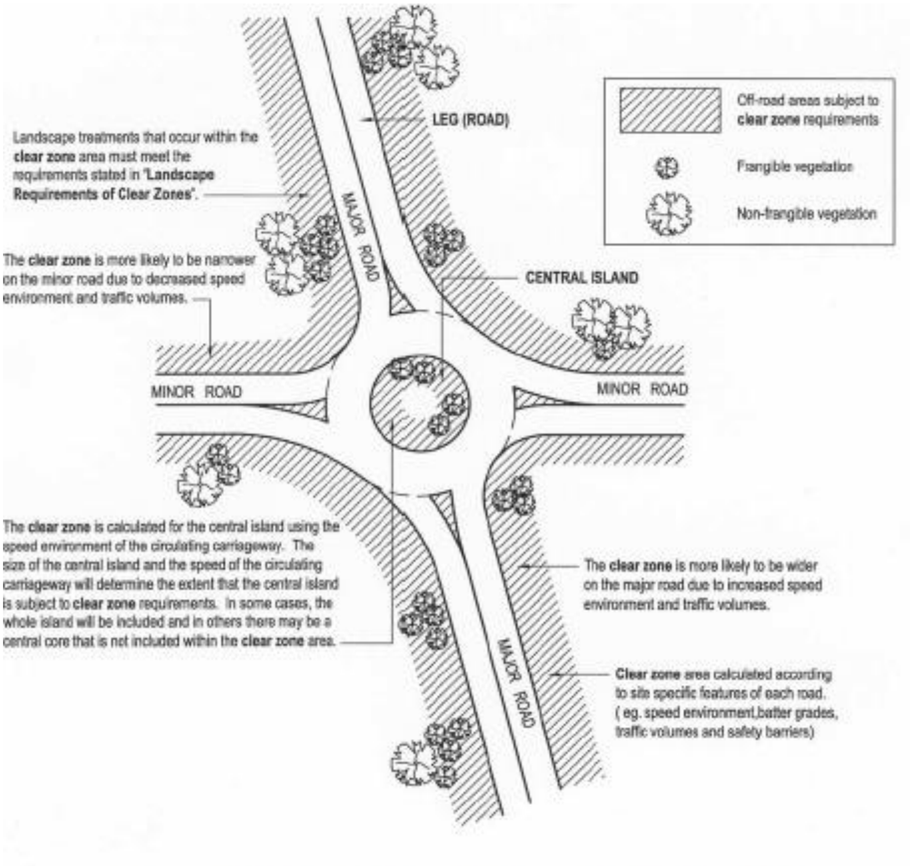


Figure C5-25: Off-road areas subject to clear zone requirements at a roundabout – Plan

Source: Main Roads 2006

Figure 2.4: Roundabout clearance zone (Department of Transport and Main Roads 2013)

2.2.4 The Vehicle

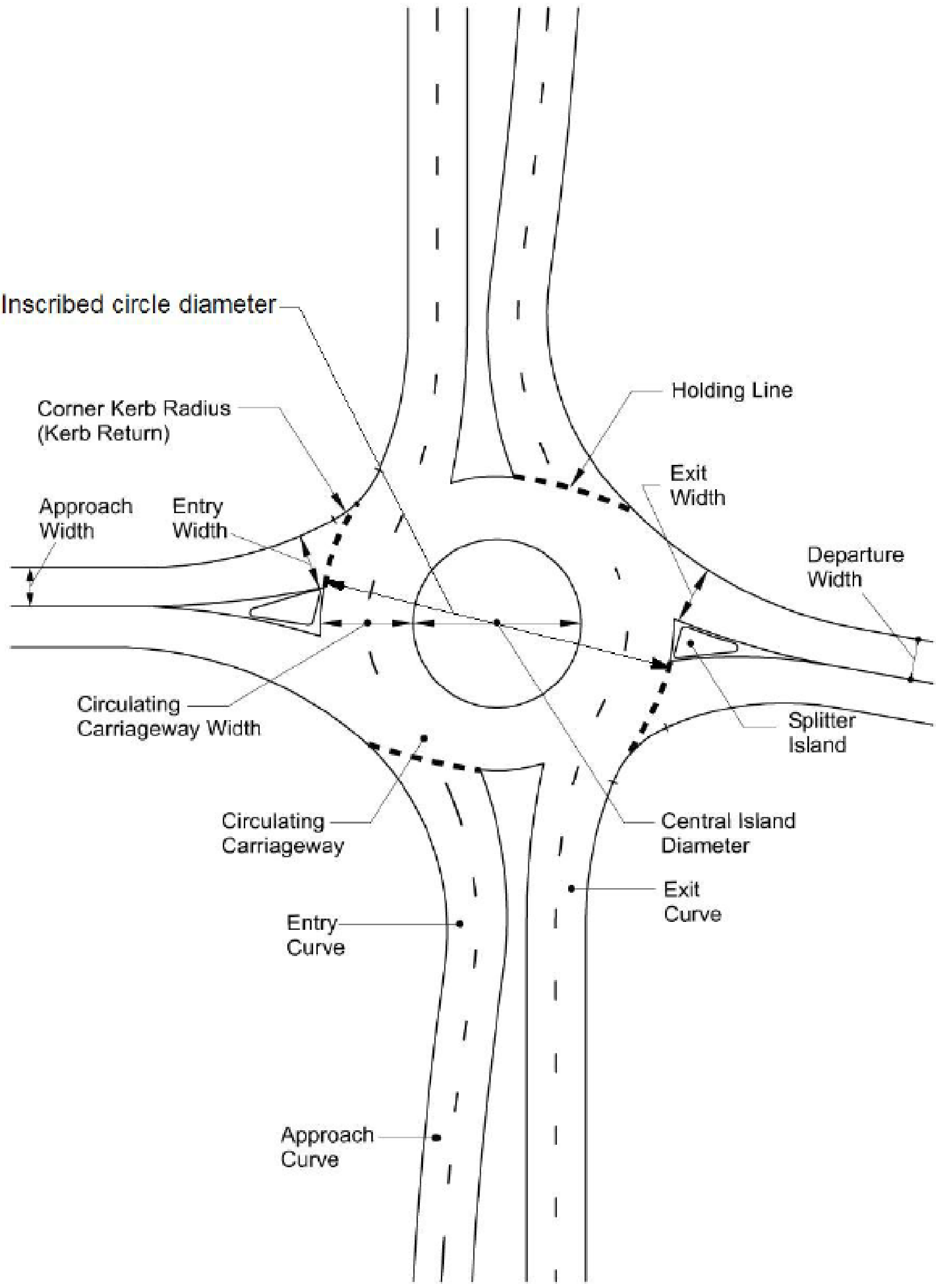
The design of the road system needs to consider the various types of vehicles that will be using the road (i.e. cars, motorcycles, bicycles, buses and rigid and articulated trucks) to allow in design for the manoeuvrability, visibility, cornering and braking of all of the likely road user types (Austroads 2009a).

2.3 Roundabout Geometry

The Austroads guidelines for designing roundabouts state that the most important geometric properties of roundabouts influencing vehicle speeds are adequate sight distance and the entry geometry (Austroads 2015b). The guidelines suggest that adequate sight distance needs to allow the driver to identify the intersection as a roundabout, understand the route required to travel through the roundabout, observe movements of other road users (including vehicles, pedestrians and cyclists) and identify an acceptable break in the circulating traffic to enter safely (Austroads 2015b). The main consideration for entry geometry is to restrict the driver into slowing down before entering the carriageway (Austroads 2015b).

Another important consideration for roundabout safety is ensuring the roundabout is easily recognisable as a roundabout and all of the associated features are clearly visible and, where possible, forgiving to road users such as motorcyclists (e.g. frangible signs and posts, skid resistant line marking etc.) (Austroads 2015b). It is also important to consider the movement of pedestrians at roundabouts. Roundabouts do not provide priority for pedestrian movement resulting in pedestrians feeling less safe when crossing the legs, particularly the exits (Austroads 2015b).

Figure 2.5 represents the geometric properties that are important when considering the road safety of roundabouts.



Source: Department of Main Roads (2006)[1].

Figure 2.5: Geometric Properties of Roundabouts (Austroads 2015b)

Some key design principles outlined in the Austroads guidelines which can be applied when assessing the performance of existing roundabouts include:

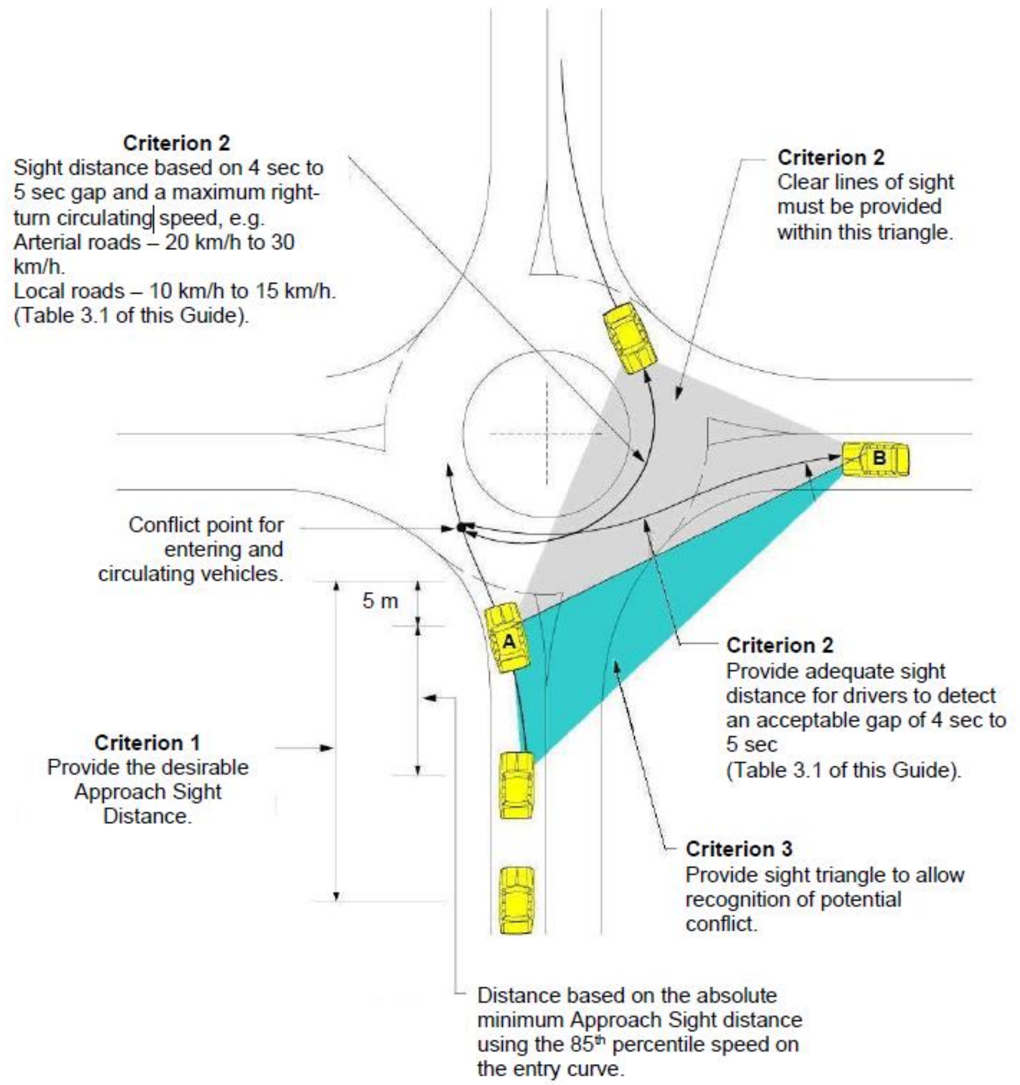
- The roundabout should be clearly visible;
- The number of legs should be limited to four where possible;

- Roundabout legs should be approximately 90° apart where possible;
- It is essential that entry speed is limited by appropriate entry curvature;
- Entry speeds should consider all road users that will be using the roundabout (e.g. cyclists and pedestrians);
- Exits should allow efficient departure;
- The inscribed circle diameter of the roundabout (periphery) must be large enough to accommodate all entries and exits without them overlapping;
- The circulating roadway needs to be wide enough to accommodate the swept paths of design vehicles plus clearance to kerbs for all movements;
- Entering drivers must have adequate sight distance to see both the circulating traffic and other traffic approaching from other legs to enter the roundabout safely; and
- Sufficient entry, circulating and exit lanes need to be provided to ensure the roundabout operates at an appropriate level of service.

2.3.1 Sight Distance

Sight distance is a fundamental element of a safe road design to ensure the driver has enough time to recognise the presence of an intersection and to comfortably slow down or stop and to see other vehicles in conflicting traffic streams to give way to and/or avoid a crash in the event of a potential conflict (Austroads 2010). Sight distance is significant both in the horizontal and vertical geometry of the road and particular road features need to be considered to ensure they do not obstruct the sight distance (e.g. trees, fences, buildings, safety barriers etc.) (Austroads 2010).

Austroads guidelines specify three sight distance criteria (criterion 1 and 2 are mandatory requirements but criterion 3 is not) that must be applied to the combination of horizontal and vertical geometry of roundabouts which affect the positioning of road features such as signs, landscaping and poles, refer Figure 2.6 for a summary of the criteria (Austroads 2015b).



Note: Values for approach sight distance are provided in Table 3.1 of AGRD Part 4A (Austroads 2010a).
Source: Adapted from Department of Main Roads (2006)[2]

Figure 2.6: Sight Distance Criteria for roundabouts (Austroads 2015b)

<u>Criterion 1</u> requires that the alignment of the approach to the intersection needs to provide the driver with good vision of the splitter island, central island and preferably the circulating carriageway (Austroads 2015b). The appropriate Average Sight Distance (ASD) should be provided to the holding line or if not possible to the nose of the splitter island on the approach as the absolute minimum (Austroads 2015b).

The Approach Sight Distance (ASD) is the minimum sight distance required for a driver on a minor road to realise the presence of an intersection. It is also desirable on the major road if possible, however, if this is difficult due to cost or impact to adjacent land/features the Stopping Sight Distance (SSD) is the minimum sight distance (Austroads 2010). The ASD is slightly different to SSD in that it is measured from the driver's eye height (1.1m) to the ground (0m) to ensure the kerb, and line markings are seen. ASD can be calculated by Equation (2-2) (Austroads 2010).

$$ASD = \frac{R_T \times V}{3.6} + \frac{V^2}{254 \times (d + 0.01 \times a)} \qquad (2\text{-}2)$$

Where:

ASD = Approach Sight Distance (m)

R_T = reaction time (s) – refer to *Austroads Guide to Road Design – Part 3: Geometric Design for values*

V = operating (85th percentile) speed (km/h)

d = coefficient of deceleration – refer *Austroads Guide to Road Design – Part 4A Unsignalised and Signalised Intersections, Table 3.1 for values*

a = a longitudinal grade in % (in direction of travel: positive for uphill, negative for downhill)

(Austroads 2010)

Criterion 2 requires the driver entering the roundabout to have sufficient sight distance to two potentially confliction movements within the roundabout, specifically; a vehicle entering the roundabout from the approach immediately to the right and a vehicle already travelling on the circulating roadway (Austroads 2015b). A critical gap (Minimum Gap Sight Distance – MGSD) of five seconds for arterial road roundabouts and four seconds for local streets is considered the minimum sight distance for a vehicle on the approach immediately to the right (Austroads 2015b). MGSDs for approaches other than the approach immediately to the right can be obtained from *Table 3.1* in *Austroads Guide to Road Design part 4B: Roundabouts* (Austroads 2015b), shown in Figure 2.7.

Table 3.1: Criterion 2 sight distances

85th percentile speed (km/h) on the approach immediately to the right, or on the circulating roadway	Criterion 2 sight distance (m)	
	Local residential street roundabout critical acceptance gap 4 sec	Arterial road roundabout critical acceptance gap 5 sec
20	22	28
30	33	42
40	44	56
50	55	70
60	67	84

Figure 2.7: Criterion 2 sight distances (Austroads 2015b)

The Minimum Gap Sight Distance (MGSD) is based on the distances drivers are willing to accept when undertaking crossing or turning manoeuvres (Austroads 2010). MGSD is measured from the point of conflict between approaching and entering vehicles back along the centre of the travel lane of the approaching vehicle and from a point 1.1m (driver's eye height) to a point 0.65m (typically vehicle indicator light) (Austroads 2010). The MGSD for a driver of an entering vehicle to see a vehicle in the conflicting streams is dependent on the length of gap being sought (critical acceptance time gap t_a) and the observation angle to the approaching traffic (Austroads 2010).

Criterion 3 is not a mandatory requirement, however it is desirable that a vehicle approaching the roundabout is able to see other entering vehicles a significant amount of time prior to reaching the holding line (Austroads 2015b). As can be seen in Figure 2.6 the sight triangle allows the approaching driver time to see an approaching car and take action to stop and give way. The sight triangle is developed by using the absolute minimum sight distance for the side of the triangle on the approach (Austroads 2015b). Austroads makes mention of concerns that some jurisdictions have found that if the sight triangle is larger than this it can encourage higher entry speeds (Austroads 2015b).

The final sight distance consideration is the Stopping Sight Distance for Trucks (SSDT). The stopping sight distance for trucks should be provided on tight horizontal curves, on or near crest vertical curves and at intersections used by a significant volume of large or special vehicles (Austroads 2015b).

2.3.2 Number of Legs and Lanes

Generally, single-lane roundabouts can operate with more than four legs at various angles, however more than four legs at angles other than 90° should be avoided for multi-lane roundabouts as it can cause confusion to the road user trying to identify the correct lane required for them to undertake their desired turning or through movement (Austroads 2015b). As a general rule, roundabouts should only be multi-lane if required for capacity as it is proven that multi-lane roundabouts increase the risk of crashes (Austroads 2015b).

The Austroads guidelines recommends that the number of entry lanes, circulating lanes and exit lanes should be consistent with the approaching roads; meaning a two lane arterial road that approaches a roundabout should enter, exit and circulate the roundabout as two lanes (Austroads 2015b).

The provision of a left turn slip lane for circumstances where there is a large volume of traffic that turns left from a particular approach can be advantageous as it avoids the requirement to install an additional entry lane (Austroads 2015b).

2.3.3 Approach and Entry Geometry

As was discussed previously, Austroads considers the most important factor that affects roundabout safety is the entry speed of the traffic which is largely controlled by the geometry of the approach and entry of the roundabout (Austroads 2015b). According to Austroads (2015b):

- limiting the speed approaching the roundabout reduces rear-end crashes;
- limiting the entry speed and angle between circulating and entering traffic reduces the relative speed between vehicles, thus reducing the frequency and severity of crashes; and
- decreasing the speed on the carriageway minimises single vehicle crashes and lower speeds also provide a safer environment for cyclists and pedestrians.

Previously in the 1993 Austroads guidelines the criteria for speed control through roundabouts was through the provision of deflection which was measured as a maximum vehicle path radius of 100m through the circulating carriageway, Figure 2.8 (Arndt 2008).

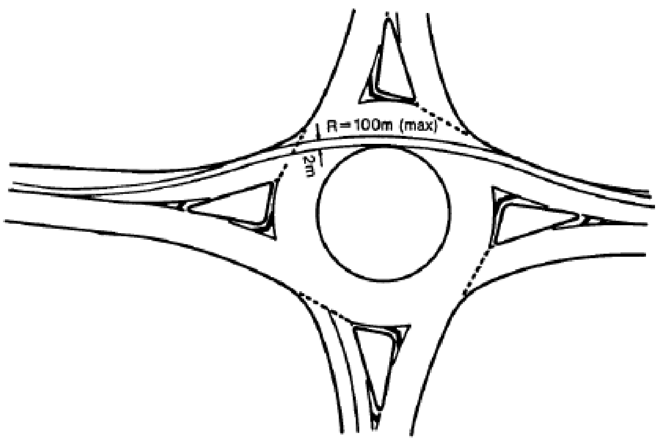


Figure 2 - Deflection Criteria for a Single Lane Roundabout (Austroads, 1993)

Figure 2.8: Deflection criteria for speed control within carriageway of roundabout (Arndt 2008)

The 2015 Austroads design guidelines uses the geometric element of entry path radius to limit the speed of vehicles on roundabouts. Rather than controlling the speed within the carriageway as is the case with the previously proposed deflection criteria the entry path radius aims to limit the vehicles speed prior to entry to the roundabout which has been proven to improve safety (Austroads 2015b).

The entry path radius for a single-lane entry is shown in Figure 2.9.

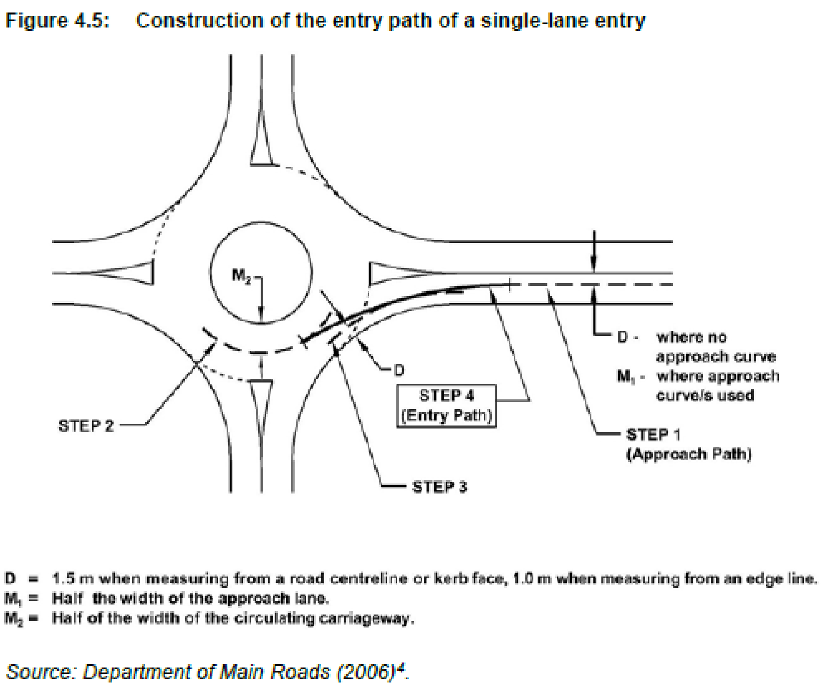
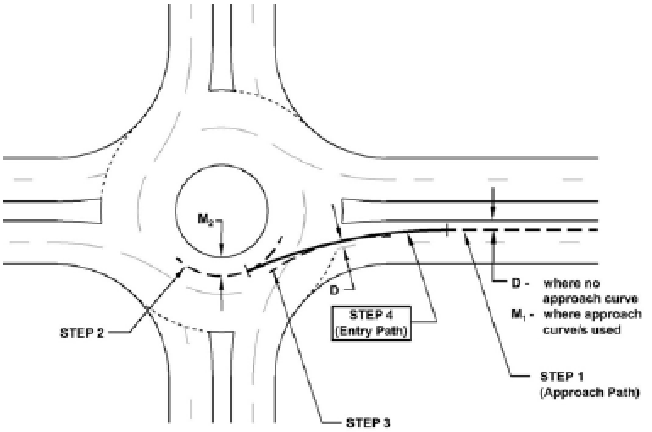


Figure 2.9: Entry path radius for speed control at roundabouts (Austroads 2015b)

The entry path radius for a two-lane entry where the vehicles remain in the correct lane is shown in Figure 2.10.

Figure 4.6: Construction of the entry path of a two-lane entry – staying in the correct lane



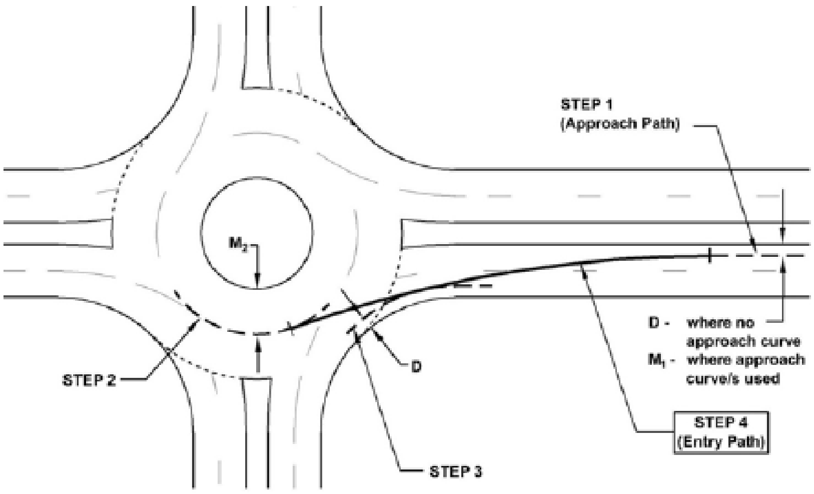
D = 1.5 m when measuring from a road centreline or kerb face, 1.0 m when measuring from an edge line.
M_1 = Half the width of the right approach lane.
M_2 = Half of the width of the inner circulating lane.

Source: Department of Main Roads (2006)[6].

Figure 2.10: Entry path radius of a two-lane entry (staying in correct lane) for speed control at roundabouts

The entry path radius for a two-lane entry where the vehicles cut across lanes is shown in Figure 2.11.

Figure 4.7: Construction of the entry path of a two-lane entry – cutting across lanes



D = 1.5 m when measuring from a road centreline or kerb face, 1.0 m when measuring from an edge line.
M_1 = Half the width of the right approach lane.
M_2 = Half of the width of the circulating carriageway.

Source: Department of Main Roads (2006)[6].

Figure 2.11: Entry path radius of a two-lane entry (cutting across lanes) for speed control at roundabouts

The maximum values for entry path radius proposed in the Austroads Guidelines: Guide to Road Design Part 4B – Roundabouts are shown in Figure 2.12.

Table 4.2: Maximum entry path radii for one and two-lane roundabouts

Desired driver speed on the leg prior to the roundabout (km/h)	Maximum entry path radius (m)[5]	
	Single-lane entries[1] Two-lane entry – staying in correct lane[2]	Two-lane entry – cutting across lanes[3]
≤ 40	≤ 55	1.9 x actual entry path radius when staying in correct lane[4]
50		1.8 x actual entry path radius when staying in correct lane[4]
60		1.6 x actual entry path radius when staying in correct lane[4]
70		1.5 x actual entry path radius when staying in correct lane[4]
80		1.5 x actual entry path radius when staying in correct lane[4]
≥ 90		1.5 x actual entry path radius when staying in correct lane[4]

1 *Construction of the entry path of a single-lane entry for roundabouts comprising one or two circulating lanes is given in Figure 4.5.*
2 *Construction of the entry path of a two-lane entry – staying in the correct lane for a two-lane roundabout is given in Figure 4.6.*
3 *Construction of the entry path of a two-lane entry – cutting across lanes for a two-lane roundabout is given in Figure 4.7.*
4 *Radius of the entry path for drivers staying in the correct lane as determined in Figure 4.6.*
5 *EDD values for the design of the entry path radii for one and two-lane roundabouts are provided in Appendix E.*

Figure 2.12: Maximum entry path radii (Austroads 2015b)

Owen Arndt also identifies in his report titled 'Speed control at roundabouts – use of maximum entry path radii' that the entry path radii work most effectively when combined with a sufficiently sized central island as discussed in the following section (Arndt 2008).

The entry and exit widths for a roundabout should be able to accommodate the swept path of the design vehicle, however, should also ensure adequate entry curvature to ensure the appropriate speed reduction prior to entering (Austroads 2015b).

2.3.4 Central Island

Austroads (2015b) recommends that the central island should be circular in shape where possible to ensure consistent speed and ease of navigation for the road user. However, sometimes elliptical, oblong or other shaped central islands are required for unusual or constrained sites which can introduce differential required speed when navigating the roundabout (Austroads 2015b).

Central islands should where possible be raised to signal to road users they are approaching a roundabout. Vegetation on the central island should not impede the sight distance of road users. In particular Austroads (2015b) recommends that for roundabouts on flat terrain the vegetation should not be higher than a car indicator light of 0.65m.

It is highlighted by Montella (2013) in a paper investigating the international design practices for roundabouts that forward visibility is often deliberately obstructed by vegetation in the central island diameter to assist the road user in differentiating the roundabout from the road environment and improve the perception of the roundabout from a distance (Montella et al. 2013).

Some factors identified in Austroads (2015b) that influence the size of the central island include the cross section of the intersecting roads, the entry design requirements to slow vehicles to a desirable entry speed and the design vehicles that need to be accommodated on the roundabout (Austroads 2015b). Essentially, the central island needs to be large enough to achieve the desired geometry but not too large so as not to encourage higher entry or circulating speeds (Austroads 2015b).

A guide provided by Austroads (2015b) for the radius of the central island is shown in Figure 2.13.

Table 4.1: Guide for selecting the minimum central island radius for a circular roundabout

Desired driver speed on the fastest leg prior to the roundabout (km/h)	Central island radius of a single-lane roundabout (m)		Central island radius of a two-lane roundabout (m)		Speed reduction treatments required prior to the entry curve[1]
	Minimum[5]	Desirable	Minimum[5]	Desirable	
≤ 40[2]	5[4]	10	8	12	No
50[2]	8	11	8	12	No
60[3]	10	12	14	16	No
70[3]	12	18	18	20	No
80[3]	14	22	20	24	Desirable
≥ 90[3]	14	22	20	24	Yes

1 *Refer to Section 4.5.2 for the various types of speed reduction treatments.*
2 *The desirable central island radii listed for these speeds generally provide sufficient size splitter islands for storage of pedestrians combined with desirable entry curvature. The minimum central island radii generally do not. In addition, the desirable values will generally produce a lower overall crash rate than what the minimum values will.*
3 *The desirable central island radii listed for these speeds provide a maximum decrease in speed between the entry curve and a right-turn on the circulating carriageway of 20 km/h. This minimises the number of potential single vehicle crashes on the circulating carriageway. The minimum central island radii are associated with values up to 30 km/h. In addition, the desirable values will generally produce lower overall crash rates than what the absolute values will.*
4 *Minimum central island radius where the design right-turn vehicle is a single unit truck is 7 m.*
5 *The minimum central island radii should typically only be selected for an initial central island radius in constrained brownfield sites. Selection of these radii may lead to some geometric design elements not complying with normal design domain criteria.*

Source: Department of Transport and Main Roads (2014) and Department of Transport and Main Roads (2015).

Figure 2.13: Guide for central island radius

The values in this Austroads table for central island radius vary if any of the following criteria are different:

- Roundabout has four legs each at 90° to each other;
- The centreline of each leg goes through the centre of the island;
- Each leg is two lanes if a two-lane roundabout;
- Kerbing exists on all legs;
- No medians on any approaches;
- Each leg has same desired speed entering the roundabout;
- The largest right-turning vehicle is a semi-trailer; and
- The design vehicle swept path remains on pavement.

  (Austroads 2015b)

Generally, if the roundabout has more than four legs, the legs are significantly more or less than 90° to each other, the centreline of the legs is located considerably to the left of the central island, there is no kerbing, medians are on some or all of the approaches or the design vehicle is larger than a semi-trailer then the roundabout central island radius should be increased (Austroads 2015b).

Austroads also identifies instances where the central island radius can be reduced from the minimum given in the table. Instances where this would be appropriate include: the roundabout has three legs; for a two-lane roundabout, some of the legs are only one lane; the desired speeds on some of the legs are significantly lower than others; or encroachment areas are used for design vehicle (e.g. garbage truck) (Austroads 2015b).

2.3.5 Circulating Carriageway

The circulating carriageway widths can be determined through the use of tables provided in the Austroads Guide to Road Design Part 4B – Roundabouts. The tables for single lane and two-lane roundabouts are in Appendix C.3.1, Figure C.3 and Figure C.4.

The table for single-lane roundabouts does not provide a carriageway width value for a 12.5m single unit truck for a central island radius of 5 or 6m which was an issue as many of the roundabouts in the top 10 fell into this range. To provide a criterion to assist in determining whether the roundabout satisfied the carriageway width requirements these values were interpolated, see Figure 2.14.

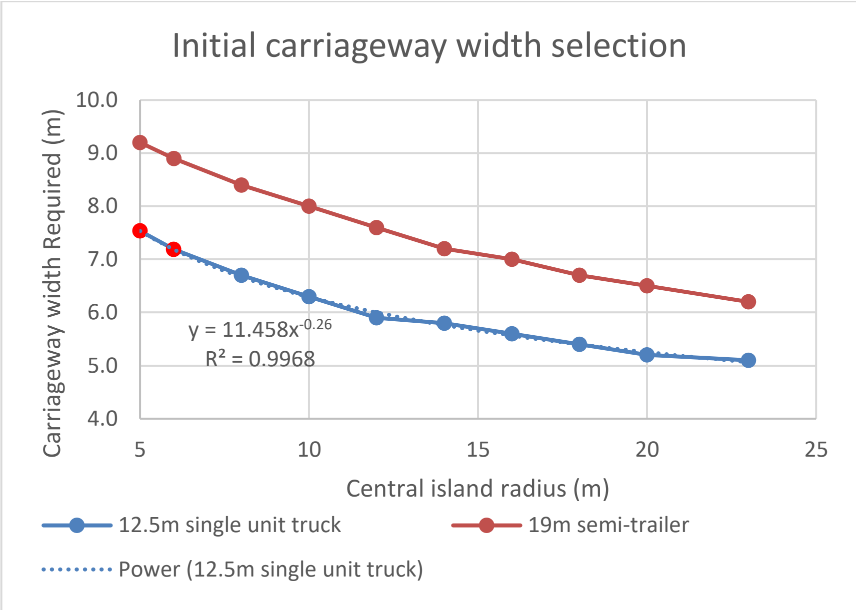


Figure 2.14: Interpolation of initial carriageway width selection for single-lane roundabout

2.3.6 Geometric Properties affecting Road Crashes

There are several researches that have investigated the effects of roundabout geometric features and crash rates. The common theme throughout the literature is that the geometry affecting the entry and circulating speed of vehicles prove the most significant. The studies and their significant findings are presented in this section.

The investigation by Anjana (2015) at urban roundabouts in Kerala, India identified that there was a direct influence of the geometric design of a roundabout on the road user's speed adoption and manoeuvring behaviour (Anjana 2015). The study used a zero-inflated negative binomial regression model to identify crash modification factors and crash prediction models for Kerala, India and identified that the geometric properties associated with an increased crash occurrence included:

- Large central island diameter – results in less deflection of circulating vehicles, increasing circulating speed and can also result in less deflection for entering vehicles increasing entry speeds;

- Excessive weaving width and weaving length – can lead to vehicles attempting to pass each other resulting in high speeds; and

- Large entry angle and entry path radius are likely to contribute to higher entry speeds.

Anjana (2015) also identified some factors that were associated with lower crash rates:

- Large exit angle aids in faster exit of vehicles clearing the roundabout carriageway;
- Provision of raised splitter island deflects entering traffic to aid in reducing the entry speed and also separates the entering and exiting vehicles; and
- Increasing circulatory roadway width, angle to next leg, exit angle and approach gradient.

The investigation done by Montella (2011) of 15 urban roundabouts in Italy identified that the most significant geometric road crash contributory factors were:

- a large radius of deflection (>100m) on the entering approach;
- a small deviation angle ($< 30°$) on the entering approach; and
- entry path radius.

Some other significant crash contributory factors identified in this investigation included excessively large:

- circulating roadway width;
- entry width;
- exit radius; and
- eccentricity of entering approach.

Owen Arndt has published a number of papers in regard to roundabout geometry over the years. In 1998, Owen conducted a study with a colleague at the Queensland University of Technology while working at the Queensland Department of Transport titled Relationship Between Roundabout Geometry and Accident Rates. This study investigated the relationship between different geometric properties and accident rates using regression analyses for one hundred roundabouts from throughout Queensland, Australia (Arndt & Troutbeck 1998). The investigation developed the following accident models;

- single-vehicle accident model – demonstrated the importance of limiting difference between expected drivers' speeds;

- approaching rear-end vehicle accident model – demonstrated the importance of limiting approach speed; and

- entering/circulating vehicle accident model – demonstrated need to minimise relative speed between entering and circulating vehicles.

Owen Arndt was also involved in the development of a geometric design software for roundabouts known as ARNDT (A Roundabout Numerical Design Tool). In some of his research he has identified that the most significant roundabout geometric properties were those that reduced the relative 85th percentile speed between entry and carriageway road users (Arndt 2001).

Geometric features found to reduce the 85th percentile speed of vehicles on the approach included providing a smaller radius approach curve and minimising entry widths (Arndt 2001).

Geometric features found to reduce the 85th percentile speed of vehicles on the carriageway included tighter deflection through the roundabout and minimising entry and exit widths (Arndt 2001).

Finally, geometric features found to reduce the angle between the entering and circulating vehicle included an increase in central island diameter and further separation of approach and next departure legs (Arndt 2001).

2.4 Cost of Road Crashes

There are two main ways to assign costs to crashes to provide a weighting enabling the ranking of intersections based on their safety performance, either by crash severity or crash type.

Austroads states that the criteria of cost of crashes by type is one of the most common methods of identifying sites that require improvement in safety performance (Austroads 2015a). Austroads suggests that assigning a cost to the crash type rather than the crash severity is more appropriate as it overcomes the problem of a single fatal crash distorting the analysis due to the extremely high cost associated with a fatal crash. Cost by crash type incorporates the concept that a particular type of crash has the potential to be a certain level of severity – Austroads gives an example of a head on collision in a high speed environment that only resulted in minor injury – even though the resulting injury was only minor it would be ranked for its potential to be a high severity crash (Austroads 2015a).

Andreassen (2001) also addresses the advantage of using cost by crash type rather than crash severity. Andreassen states that the frequency of fatal crashes is statistically quite rare and when used over a short period of time does not accurately represent the expected frequency of crashes in previous or subsequent years. Increasing the study period is usually not an option as it introduces other problems such as changes to traffic conditions and road features at the location which could also influence the frequency of crashes (Andreassen 2001). Another issue with assigning costs based on crash severity is that the crash is classified according to the most severe injury resulting from the crash. This does not distinguish between a fatal crash where one person was killed and a fatal crash where one or more people were killed and others seriously injured (Andreassen 2001).

Andreassen (2001) identifies the two main advantages of using crash type as the criteria for cost being that the distribution of each severity level to each crash type is statistically stable over time meaning only the number of crash types need to be considered and the effects are reported in terms of changes in specific crash types rather than just the total number of crashes.

Andreassen (2001) explains how the crash costs for crashes by type were developed and some of the assumptions made for cost data:

- 1996-98 Australian life expectancy tables, by age and gender, used in calculating future productivity;
- Employment percentages, hours worked and average earnings by age group and gender from ABS, 1999;
- Unpaid hours by age group and gender from ABS, 1997 – time spent on domestic duties, childcare, purchasing, and voluntary work;
- Major labour costs, ABS 1997, taken at 16% - note: employer superannuation contributions increased to 8% in July 2000;
- No paid work from 75yrs onward. Unpaid hours:
    - For 75 to 84yrs assumed 2/3 of those for 65 to 74yrs;

    - For 85 to 95yrs assumed to be 1/3 of those for 65 to 74yrs; and
    - For 95yrs on, assumed to have no value.
- From age 60 onward females were assumed to have same value per hour for work as males;
- Discount rate for lost future productivity 5%;
- Prospect of persons with disabilities to get casual work – 30%; and
- Vehicle repair costs and delay costs assumed to increase in line with increase in average wages.

Note: average weekly earnings (AWE) are not the same as average income for a whole community – a number of exclusions from the AWE survey give results likely to be lower than average community income

After future productivities were derived for each age and gender they were mapped on to the age distribution of road users in crashes

2.4.1 Property Damage Crashes

Andreassen (1999) addresses the importance of including Property Damage Only (PDO) crashes in analysis for identifying locations that require treatment to improve the safety performance. He notes that if only casualty crash data is used to identify locations of low safety performance then fewer locations would be identified as needing treatment until enough casualty data was gathered to identify the site as requiring treatment. Using PDO crashes in the analysis provide an indication of when a particular location is becoming unsafe before people are injured or killed at that location in a more serious crash. This allows the need for improvement to be identified earlier, rather than having to wait until injury or fatality data shows a particular location to be an issue (Andreassen 2001).

2.5 Highway Safety Manual – Safety Performance Measure Methods

There are several performance methods proposed in the Highway Safety Manual to assist in ranking intersections to identify the poorer performing roundabouts (AASHTO 2010a). Usually the different sites are separated into reference populations such as: type of traffic control, number of approaches, area type (e.g. urban, suburban, rural), traffic volume ranges or terrain (AASHTO 2010a). Although detailed examination of all of the Toowoomba roundabouts has not been undertaken, the few reference populations that may be appropriate include: area type (e.g. urban or suburban), traffic volume or particular geometric properties that can categorise the roundabouts.

There are thirteen different performance measure methods proposed in the Highway Safety Manual that can be used to rank the sites (AASHTO 2010a). Each of these proposed methods require different data and inputs as illustrated in Figure 2.15.

	Data and Inputs				
Performance Measure	**Crash Data**	**Roadway Information for Categorization**	**Traffic Volume[a]**	**Calibrated Safety Performance Function and Overdispersion Parameter**	**Other**
Average Crash Frequency	X	X			
Crash Rate	X	X	X		
Equivalent Property Damage Only (EPDO) Average Crash Frequency	X	X			EPDO Weighting Factors
Relative Severity Index	X	X			Relative Severity Indices
Critical Rate	X	X	X		
Excess Predicted Average Crash Frequency Using Method of Moments[b]	X	X	X		
Level of Service of Safety	X	X	X	X	
Excess Predicted Average Crash Frequency Using Safety Performance Functions (SPFs)	X	X	X	X	
Probability of Specific Crash Types Exceeding Threshold Proportion	X	X			
Excess Proportion of Specific Crash Types	X	X			
Expected Average Crash Frequency with EB Adjustment	X	X	X	X	
Equivalent Property Damage Only (EPDO) Average Crash Frequency with EB Adjustment	X	X	X	X	EPDO Weighting Factors
Excess Expected Average Crash Frequency with EB Adjustment	X	X	X	X	

[a] Traffic volume could be AADT, ADT, or peak hour volumes.
[b] The Method of Moments consists of adjusting a site's observed crash frequency based on the variance in the crash data and average crash counts for the site's reference population. Traffic volume is needed to apply Method of Moments to establish the reference populations based on ranges of traffic volumes as well as site geometric characteristics.

Figure 2.15: Summary of Data Requirements for Performance Analysis Methods (AASHTO 2010a)

Road crash data for roundabouts in Toowoomba was obtained through the Department of Transport and Main Roads. Roadway information was sourced through site visits as well as satellite imagery. Traffic volume data was obtained through the Toowoomba Regional Council and all roundabouts except two have relatively recent traffic volume data. As is addressed in the Highway Safety Manual, Volume 3, pp.12-47, there has not yet been enough research to develop a predictive method for roundabouts (AASHTO 2010b). This means the use of any of the performance methods that require Calibrated Safety Performance Functions are not possible.

Another aspect to consider when choosing the performance measure methods is the stability of the methods. The two main considerations that can affect the stability of the methods are the effects of regression-to-the-mean (RTM) bias and performance thresholds (AASHTO 2010b). The RTM bias refers to the natural fluctuation of crash frequencies at a site over time and the performance threshold is a value that provides a reference point and the sites that yield a performance score less than the threshold value can be studied in further detail (AASHTO 2010b).

The possible performance measure methods that can be used to rank the crash data are summarised in Table 2.1 which highlights the data required to use the method and the stability of the method.

Table 2.1: Data Requirements and Stability of Performance Measure Methods

	Data and Inputs				Stability	
Performance Measure	**Crash Data**	**Roadway Information**	**Traffic Volume**	**Other**	**Accounts for RTM bias**	**Estimates Performance Threshold**
Average Crash Frequency	✓	✓				
Crash Rate	✓	✓	✓			
Equivalent Property Damage Only (EPDO) Average Crash Frequency	✓	✓		EPDO Weighting Factors		
Relative Severity Index	✓	✓		Relative Severity Indices		✓
Critical Crash Rate	✓	✓	✓		Considers data variance but not RTM bias	✓
Excess Predicted Average Crash Frequency Using Method of Moments	✓	✓			Considers data variance but not RTM bias	✓
Probability of Specific Crash Types Exceeding Threshold Properties	✓	✓			Considers data variance but not RTM bias	✓
Excess Proportion of Specific Crash Type	✓	✓			Considers data variance but not RTM bias	✓

These performance measures are outlined in the sections below.

2.5.1 Average Crash Frequency

The average crash frequency method is a simple ranking method which ranks the sites according to the total number of crashes either by type or by severity, or both (AASHTO

2010a). Due to the simplicity of the method this method is usually used as an initial ranking to identify a group of sites for further analysis. The sites are usually ranked by the total number of crashes, fatal and injury crashes, PDO crashes or a combination thereof (AASHTO 2010a).

2.5.2 Crash Rate

The crash rate method normalises the number of crashes in relation to the traffic volume experienced at the intersection (AASHTO 2010a). The main limitation with this method is that if intersections have considerably different traffic volumes it is difficult to make comparisons between them and intersections with low traffic volumes and low collisions will be prioritised by mistake (AASHTO 2010a).

2.5.3 Equivalent Property Damage Only (EPDO) Average Crash Frequency

The Equivalent Property Damage Only (EPDO) Average Crash Frequency method assigns weighting factors (calculated relative to the Property Damage Only (PDO) crashes) to the road crashes based on the severity of the road crashes (AASHTO 2010a).

One of the biggest limitations of this particular method is the significant influence a fatal crash has on the ranking process due to the significant weighting factor (AASHTO 2010a). In some instances, to avoid this overemphasis on fatal crashes, the fatal and injury crashes have been combined in the one category (AASHTO 2010a).

2.5.4 Relative Severity Index

The Relative Severity Index method uses societal crash costs based on the type of crash that are assigned to each crash at each site to develop a Relative Severity Index (RSI) (AASHTO 2010a). The average RSI cost for each intersection is compared with the average RSI cost for the respective population to determine which intersections exceed the average and to rank the intersections (AASHTO 2010a). This method is simple and includes the collision type and crash severity as factors in the ranking of the intersections. However, one of the most significant limitations of this method, similar to the EPDO Average Crash Frequency method, is the possibility of overemphasising locations with a small number of severe crashes (AASHTO 2010a). This method also does not account for traffic volume so will incorrectly prioritise low volume, low collision sites (AASHTO 2010a).

2.5.5 Critical Crash Rate

The Critical Rate method takes the Crash Rate method a few steps further by considering data variance and establishes a threshold value for comparison in the ranking of the intersections. Essentially the crash rates calculated in section 2.5.2 are compared with a critical crash rate unique to each site to identify intersections that exceed this critical rate for further investigation (AASHTO 2010a).

2.5.6 Excess Predicted Average Crash Frequency Using Method of Moments

The Method of Moments method determines the potential for reduction in the number of crashes at the particular intersection. This method partially accounts for regression to the mean with the adjustment to the observed average crash frequency which is compared with the average crash frequency for the reference population to identify the potential for improvement (PI) (AASHTO 2010a). One of the most significant limitations is that the method does not account for traffic volume.

The sites can be ranked from highest to lowest PI value, where a negative PI value is possible, indicating a very low potential for crash reduction (AASHTO 2010a).

2.5.7 Probability of Specific Crash Types Exceeding Threshold Properties

The Probability of Specific Crash Types Exceeding Threshold Properties method determines the probability that the true proportion, p_i, of either a crash type or severity at a particular location is greater than the threshold proportion for the respective crash type, p_i^* (AASHTO 2010a). One of the main limitations of this method is that it does not account for traffic volume and some sites may be prioritised incorrectly due to unusually low numbers of non-target crash types (AASHTO 2010a).

2.5.8 Excess Proportion of Specific Crash Type

The Excess Proportion of Specific Crash Type method also uses the proportion of a particular type of crash at each intersection compared with a threshold proportion to determine which intersections exceed the threshold proportion to identify where a specific type of crash is overrepresented (AASHTO 2010a). The two main limitations of this method are that it does not consider traffic volume and there is the possibility that sites with unusually low frequency of non-target crashes can increase the proportion of the target crash type thus mistakenly identifying it as higher than the threshold proportion.

2.6 Crash Prediction Models

Crash prediction models are used to estimate the expected crash frequency for a particular road feature and to identify factors (such as geometrical, environmental or operational), that influence the frequency of crashes (Anjana 2015).

There are several methods for developing these prediction models, however, the Poisson, negative binomial and zero-inflated models are the most common for prediction of crash frequency (Anjana 2015).

A recent study (Anjana 2015) identified geometric crash contributory factors and developed crash prediction models for the urban roundabouts in the state of Kerala, India. This study by S. Anjana identified the zero-inflated negative binomial regression model as the best model for predicting crash frequency of roundabout approaches (Anjana 2015).

The study considered crash data obtained from the State Crime Records Bureau for 2008 – 2010, geometric data from survey and CAD drawings and traffic volume data collected by manual and video graphic methods for 20 roundabouts (Anjana 2015). The crash data included the number of crashes at each leg of the roundabout, the crash severity, the type and number of vehicles involved and the date and time of the occurrence (Anjana 2015). The geometric data collected included the inscribed circle diameter – measure between outer edges of circulating roadway, entry and exit width, entry and exit angles and approach and departure widths (Anjana 2015).

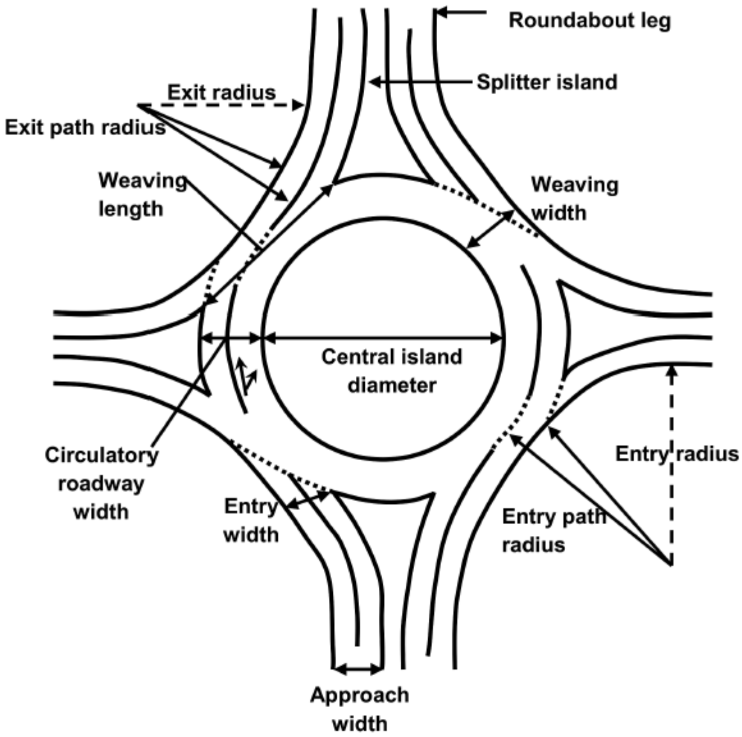


Figure 2.16: Geometric features of a roundabout (Anjana 2015)

The general equation for the relationship between the explanatory variables and crash frequency can be expressed by Equation (2-3).

$$A = kQ_1^{\alpha}Q_2^{\beta}e^{(\sum g_i G_i)} \tag{2-3}$$

Where:

A = crash frequency;

Q_1 and Q_2 = entering and circulating flows, respectively;

G_i = geometric variables; and

k, α, β and g_i = parameters of model.

(Anjana 2015)

Anjana (2015) found that the best model for the data was the zero inflated negative binomial and developed the three final crash prediction models as in Equations (2-4), (2-5) and (2-6):

$$Total\ crashes = e^{0.963+0.010AV+0.018CID-0.106CRW+0.048WW+0.023WL+0.002EPR-0.005ANL-0.465RI-0.460B+0.040M} \tag{2-4}$$

$$Injury\ crashes = e^{0.117+0.017AV-0.060CRW+0.013EA-0.019ExA+0.027WL+0.001EPR} \tag{2-5}$$

$$PDO = e^{-0.900+0.004AV+0.015RS+0.008CID+0.015EA+0.003ExR-0.092AG} \tag{2-6}$$

Where:

AV = Approach Volume;

CID = Central Island Diameter;

CRW = Circulating Roadway Width;

WW = Weaving Width;

WL = Weaving Length;

EPR = Entry Path Radius;

ANL = Angle to the Next Leg;

EA = Entry Angle;

ExA = Exit Angle;

ExR = Exit Radius;

RS = relative approach and circulating speed;

AG = Approach Gradient; and

RI, B and M = splitter island type (raised, barricade with marking and marking only).

These models predict the crash frequency of roundabouts in Kerala, India using the explanatory variables (particular geometric attributes) that are most significant in their effect on the safety of the roundabouts (Anjana 2015). These models can also be used to determine if a change in a particular geometric property would improve the safety of the roundabout and give a quantitative value as to how effective it may be.

2.7 Crash Modification Factors

Crash Modification Factors (CMFs) are a multiplication factor used to calculate the expected number of crashes if a remedial measure is implemented at a particular site (Anjana 2015). There are two main methods that can be used to develop CMFs which are both observational studies. These are: before-after studies and cross-sectional studies (Anjana 2015).

Before-after studies are considered the industry standard for the development for CMFs, and usually require a large number of comparable roundabouts for treatments to be implemented and the effects recorded (Anjana 2015). Some of the common treatments investigated include: police enforcement, policy implementation, traffic management measures, operation change and resurfacing projects (Anjana 2015). However, sometimes it is not possible to find sufficient roundabouts of comparable attributes to conduct the treatment on (Anjana 2015).

Cross-sectional studies use regression methods on a large sample of roundabouts that have a range of different attributes to estimate crash frequency. This approach allows a more comprehensive study of the different crash contributory factors to quantify what effect they have on the road safety at roundabouts (Anjana 2015).

In the study by Anjana, a cross-sectional approach was used to develop the CMFs for each of the roundabout variables (geometric and traffic) that the crash prediction models incorporated (discussed in the previous section 2.6) (Anjana 2015). The base model required to generate the CMFs used the existing crash frequency before any safety treatments and geometric design values from the Indian Roads Congress guidelines for design of rotary intersections (Anjana 2015). Essentially the ratio of after treatment crashes and before treatment crashes will give the CMF for each of the particular geometric variables changed. The CMF results obtained by Anjana (2015) indicated:

- The following geometric properties increase the entry or circulating speed of vehicles, increasing the probability of crashes:
    - A large central island diameter which results in there being less deflection of circulating vehicles;
    - Reduction in entry deflection; and
    - A large entry angle and entry path radius.
- Some changes to geometric variables that showed an improvement in crash rates were:
    - having a raised splitter island; and
    - increasing: the circulatory roadway width, angle to next leg, exit angle and approach gradient.
- The presence of a raised splitter island of sufficient length and the presence of gradient were both factors that improved crash rates by reducing the entry speed of vehicles.

The CMFs developed in the study by Anjana are shown in Figure 2.17 also compared with CMFs developed in a US study (Anjana 2015).

Table 7. Comparison of CMFs Developed Using Data from the United States and India

Design feature	(NCHRP 2010) Entering-circulating crashes	Exiting-circulating crashes	Approach crashes	Present study Total crashes	Injury crashes	PDO
Entry radius	1.010	—	—	—	—	—
Entry path radius	—	—	—	1.002	1.002	—
Entry width	1.052	—	—	—	—	—
Approach half width	—	—	1.031	—	—	—
Inscribed circle diameter	—	1.022	—	—	—	—
Central island diameter	0.922	1.014	—	1.022	—	1.009
Circulatory roadway width	—	1.117	—	0.904	0.935	—
Angle to next leg	0.973	—	—	0.995	—	—

Figure 2.17: Crash Modification Factors (CMF) developed by Anjana and compared to a US study (Anjana 2015)

The methodology for using the crash modification factors is as follows:

1. Estimate the expected number of crashes for the base condition (N_{base})

2. Adjust the value obtained from the base model to reflect the existing conditions using Equations (2-7) and (2-8):

$$N_{w/o} = N_{base} \times CMF_c \tag{2-7}$$

$$CMF_c = CMF_1 \times CMF_2 \times \ldots CMF_n \tag{2-8}$$

Where:

$N_{w/o}$ = Crash count for existing conditions; and

CMF_c = combined CMF for all observed features different from base conditions.

3. Specify a design change and identify corresponding CMF.

4. Estimate number of crashes corresponding to specified change (N_w) using Equation (2-7) and new CMF_c values that reflect design change.

5. Compute percentage change in crashes, Equation (2-9).

$$Percentage\ change\ in\ crashes = \frac{N_w - N_{w/o}}{N_{w/o}} \times 100 \tag{2-9}$$

(Anjana 2015)

Essentially if the result is a negative value the number of crashes will be reduced and the proposed treatment is acceptable (Anjana 2015).

2.8 Road Safety Audit and Crash Investigation

The Austroads guidelines outline how to conduct a road safety audit to determine the crash potential and safety performance of a road or intersection. The road safety audit is most effective when applied to a project in the design stage, however is also useful when applied to a design change of an existing road feature and should be undertaken by people with appropriate experience and training (Austroads 2015b). A road safety audit goes further than simply complying with the relevant standards (which are often only the minimum requirements for common situations) and instead applies a fit for purpose assessment on the particular road element (Austroads 2015b). It is important to gather all of the available background information such as traffic volumes, previous road safety reports or any plans and drawings available (Austroads 2009b).

Site visits should be conducted both during daylight and at night to identify any potential safety issues during the two conditions (Austroads 2009b). It is also important to conduct the inspection from the point of view of each likely type of road user from each possible approach (Austroads 2009b). Photographs of the site provide useful tools for later reference.

A road safety audit on an existing road should be carried out as well as a crash investigation to obtain the best results in regard to the safety performance of the road. The aim of a road safety audit on an existing road is to proactively identify any safety issues that could lead to future road crashes so that treatments can be implemented that may prevent road crashes occurring (Austroads 2009b). A crash investigation in comparison is a study of past crashes to identify factors that contributed to those crashes and attempt to implement treatments to improve the safety (Austroads 2009b). By conducting a road safety audit in conjunction with a crash investigation, some features such as a specific pole on the outside of a curve that has not previously been a contributing factor in an crash may be identified as a safety issue in the audit but wouldn't have been identified if only the crash investigation had been undertaken (Austroads 2009b). When determining what features may be a potential hazard, a simple test is to ask the question; 'What type of crash, or what additional injury, could occur as a result of this feature?' (Austroads 2009b).

Once potential safety issues have been identified it is important to apply some kind of risk prioritisation to assist in getting remedial treatments implemented to improve the safety of the particular road element (Austroads 2009b). The Road Safety Risk Manager (RSRM) is an evidence based crash risk model developed by ARRB Group in association with Austroads which allows prioritisation of the possible remedial treatments of potential safety issues to maximise the crash risk reduction with the minimum expenditure (Austroads 2009b).

2.9 Remedial Treatments

Austroads Guide to Road Safety Part 8: Treatment of Crash Locations provides some guidance on selecting countermeasures for road features that have been identified as having contributed to crashes. The criteria provided in Austroads (2015a) includes:

- Technical feasibility: can countermeasure provide an answer to safety problems which have been diagnosed and does it have a technical basis for success?
- Economic efficiency: is the countermeasure likely to be cost effective?
- Affordability: can it be accommodated in the program budget; if not, should it be deferred, or should a cheaper interim alternative be adopted?
- Acceptability: does the countermeasure clearly target identified problems and will it be readily understandable by community?
- Practicability: is there likely to be a problem of non-compliance?
- Political and institutional acceptability: is the countermeasure likely to attract political support and will it be supported by the organisation responsible for its installation and ongoing maintenance?
- Legal conformity; is the countermeasure compatible and consistent with other strategies?

3.0. METHODOLOGY

An extensive amount of research on the current literature relating to roundabout design, road crashes at roundabouts and the significant contributing factors to these road crashes was undertaken. Particular attention was given to the analysis of significant contributory factors to road crashes, in particular the geometrical features that potentially contributed to road crashes, and how these factors relate to each other. This will assist in determining what factors may be contributing to the road crashes seen at the roundabouts in Toowoomba.

3.1 Roundabout Classification and Road Crash Data

For the purposes of an identification convention for this dissertation the 49 roundabouts were classified based on their location in the Toowoomba area. The city of Toowoomba was divided into four quadrants using the two main streets, Ruthven Street and James Street, Figure 3.1. The four quadrants were NW, NE, SW and SE and each of the roundabouts were numbered within each of these quadrants using the quadrant as the prefix.

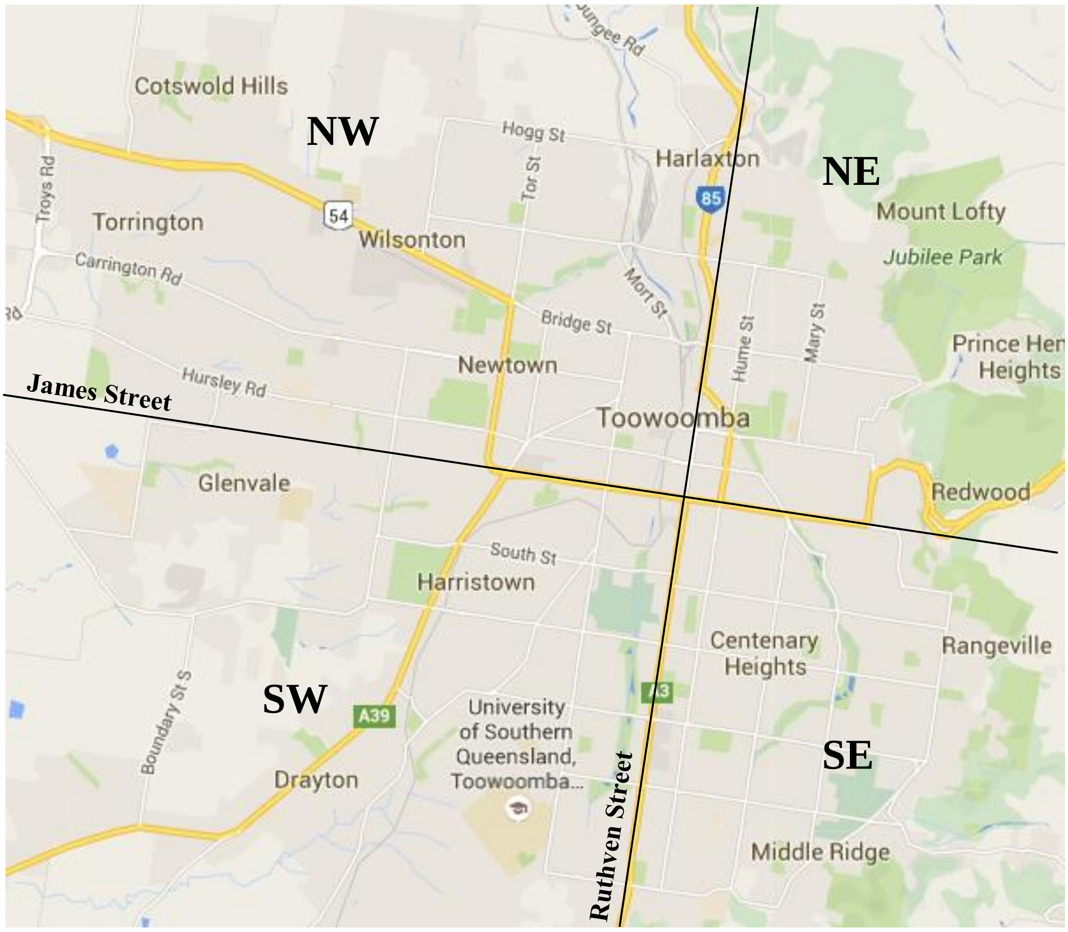


Figure 3.1: Roundabout Identification Convention – figure adapted from (Google Maps 2016)

Roundabouts in North West (NW) quadrant are:

NW1 Heinemann Road, Troys Road, Toowoomba-Cecil Plains Road and Carrington Road

NW2 Hursley Road and Corfield Drive

NW3 Hursley Road and McDougall Street

NW4 Hursley Road and Greenwattle Street

NW5 Hursley Road, Anzac Avenue and Holberton Street

NW6 Anzac Avenue, Russell Street and West Street

NW7 North Street and Tor Street

NW8 North Street and Holberton Street

Roundabouts in the North East (NE) quadrant are:

NE1 Jellicoe Street and Stuart Street

NE2 Bridge Street and MacKenzie Street

NE3 Bridge Street and Curzon Street

NE4 Margaret Street and Kitchener Street

NE5 Margaret Street and Lindsay Street

NE6 Herries Street and Mary Street

NE7 Herries Street and MacKenzie Street

NE8 Herries Street and Curzon Street

NE9 James Street and Burke Street

Roundabouts in the South West (SW) quadrant are:

SW1 Alderley Street and Drayton Road

SW2 Stenner Street, Luck Street and Drayton Road

SW3 Gorman Street and Wuth Street

SW4 Alderley Street, Walters Drive and Spencer Street

SW5 South Street and Greenwattle Street

SW6 Glenvale Road and Greenwattle Street

SW7 Glenvale Road and McDougall Street

SW8 Glenvale Road and Boundary Street

Roundabouts in the South East (SE) quadrant are:

SE1	Perth Street and Hume Street
SE2	Perth Street and Geddes Street
SE3	Perth Street and Ramsay Street
SE4	Perth Street and MacKenzie Street
SE5	Long Street and Hume Street
SE6	Long Street and Geddes Street
SE7	Long Street and Ramsay Street
SE8	Long Street and MacKenzie Street
SE9	Long Street, Tourist Road and High Street
SE10	South Street and Hume Street
SE11	South Street and Geddes Street
SE12	South Street and MacKenzie Street
SE13	Alderley Street and Hume Street
SE14	Alderley Street and Ramsay Street
SE15	Alderley Street and MacKenzie Street
SE16	Alderley Street and Rowbotham Street
SE17	Ballin Drive, MacKenzie Street and Waterbird Drive
SE18	Stenner Street and Hume Street
SE19	Stenner Street and Ramsay Street
SE20	Stenner Street and MacKenzie Street
SE21	Spring Street and Hume Street
SE22	Spring Street and Ramsay Street
SE23	Spring Street and MacKenzie Street
SE24	Spring Street and Rowbotham Street

Road crash data for Toowoomba roundabouts was obtained from the Department of Transport and Main Roads (DTMR) Queensland and included the following data:

- Fatal crashes to 31 December 2013;
- Hospitalisation crashes to 30 September 2013;
- Medical Treatment and Minor Injury crashes to 31 December 2011; and
- Property Damage Only crashes to 31 December 2010 (no further data available).

Austroads suggests that a study period of five years typically provides statistical reliability. Periods longer than this are more likely to have variance in traffic volumes and changes in road features (Austroads 2015a). With this in mind the study period was selected to be five years. Ideally, the study period would include complete data from all severity levels across the full five years. However, the most recent 5 year period with five full years of data that was available for Toowoomba was 2006 to 2010 which was not very recent. The ranking methodology as discussed in the following sections was not dependent on the crash severity so it would not be expected that the data would be significantly skewed by including data from some severity levels and not others. As such the study period was selected to be between 2006 and 2013 inclusively which allowed five full years of data across all crash severity levels and the additional more recent data from 2011 to 2013. The preliminary data analysis identifying trends of crashes at roundabouts in Toowoomba was done using the full set of data from 2006 to 2010 as these results were sensitive to crash severity distribution.

Toowoomba has a total of 49 roundabouts however six (6) roundabouts have been excluded from the ranking. Three (3) of the roundabouts do not have any crash data. These are; NW2 Hursley Road and Corfield Drive, SE16 Alderley Street and Rowbotham Street and SE24 Spring Street and Rowbotham Street. By comparing 2006 imagery with 2016 imagery, each roundabout was visually inspected to determine if there had been any significant changes to the geometry of the roundabout during the study period. It was determined that three (3) of the roundabouts, NW5, NE8 and SW4, had significant changes during this time.

NW5 Hursley Road, Anzac Avenue and Holberton Street was significantly changed in 2007 by adding in two lanes on Anzac Avenue, changing the central island shape and diameter, providing a turn left lane from Holberton Street and providing a bypass for traffic travelling southbound on Anzac Avenue, refer Figure 3.2. In addition to these works, this roundabout also had works done in 2015 to improve the road surface, significant vegetation was removed to improve sight distance for approaching traffic on the Hursley Rd approach, the entry geometry on the Anzac Avenue southbound approach was altered and more warning signage was installed to try and reduce entry speeds particularly on the northbound lane of Anzac Avenue. When crash data becomes available it is suggested that this roundabout be reviewed to determine how it is now performing since the most recent works in 2015. During the period 2006 to 2013 there were 59 crashes at this roundabout which is more than double the number of crashes than any other roundabout in Toowoomba. This roundabout should be regularly reviewed for safety performance to try and reduce the frequency of the crashes.

Figure 3.2: Significant changes to roundabout NW2. 2006 (left) vs 2016 (right) (Google Maps 2016)

NE8 Herries Street and Curzon Street and SW4 Alderley Street, Walkers Drive and Spencer Street roundabouts were both only constructed post 2006. Previously NE8 was a cross intersection with give way signs and SW4 was a T-intersection before Walkers Drive was constructed as part of a new industrial subdivision which led to the installation of the roundabout.

Due to the significant changes to these three (3) roundabouts during the study period it was decided the data available was not an accurate representation of the current roundabout in use and so they would not be included in the ranking process. Some other roundabouts had less significant changes such as the addition of a trafficable central island apron on roundabouts SE5, SE10 and SE14; the addition of a keep clear on roundabout NE4; the adjustment of a right turning lane for the west bound exit lane of roundabout SW6 into a corner shop and the addition of two lanes on the southbound lanes on Hume Street at roundabout SE21.

3.2 Preliminary Analysis of Road Crash Data

The preliminary analysis of the data used all of the data from all forty-nine (49) roundabouts to provide an overall picture of crash trends at roundabouts in Toowoomba. Graphs were produced for:

- the frequency of crash severity per year;
- the frequency and distribution of crash severity at roundabouts;
- the frequency and distribution of crash types at roundabouts;
- the frequency and distribution of the road user involved; and
- the frequency per month, day and hour.

From these results some basic conclusions were drawn in regard to the crash trends at roundabouts in Toowoomba.

3.3 Road Safety Methodologies for Ranking Roundabouts

The Highway Safety Manual as well as the Austroads guidelines included several methods for determining roundabouts that could be improved. The methods considered various factors in addition to the road crashes including a mixture of: traffic volume, crash severity and type of crash. The two methods selected from the Highway Safety Manual to be used in the ranking of the roundabouts were the Critical Crash Rate and the Relative Severity Index (RSI) method. The Excess Proportion of Specific Crash Type method was also applied to the identified top 10 roundabouts to determine whether any of the roundabouts experienced an excess of either angle, hit object or rear-end crashes.

The data period used for the road safety performance calculations included data from 2006 to 2013. This was to allow for the inclusion of more recent data. The two selected methods do not rely on the crash severity of each crash so it was considered appropriate to include the additional data from 2011 to 2013 even though not all severity levels were available for these years.

As discussed in the literature review, the main limitation of these two methods is that the critical crash rate method may prioritise sites with low volume and low collisions, and the RSI method may prioritise sites with a small number of severe crash types. To reduce the effect these limitations had on the ranking results; the roundabouts that had less than the average number of crashes (5 crashes) were excluded from the ranking. There was some trial and error required to determine a threshold of crashes for inclusion and it was found that excluding roundabouts with less than 5 crashes ensured roundabouts weren’t being prioritised incorrectly.

3.3.1 Critical Crash Rate

The crash rate method normalises the number of crashes in relation to the traffic volume of the intersection (AASHTO 2010a). The critical crash rate establishes a threshold value for comparison in the ranking of the intersection to identify intersections that exceed the critical rate for further investigation (AASHTO 2010a).

The traffic volume data was sourced from the Toowoomba Regional Council and was received in two formats. Average Daily Traffic (ADT) values for each leg of the roundabouts captured using MetroCount equipment which captured all vehicles travelling on each leg (entering and exiting) and CAMDAS video traffic count data which provided traffic volume data for entering vehicles on each leg of the intersection as well as pedestrians between the hours of 6am and 6pm. This data was useful in identifying traffic volume distribution between the different legs of the roundabouts.

The traffic volume was measured as Million Entering Vehicles (MEV), Equation (3.1):

$$MEV = \frac{TEV}{1{,}000{,}000} \times n \times 365 \tag{3.1}$$

Where:

MEV = Million Entering Vehicles;

TEV = Total Entering Vehicles per day (sum of major and minor street Annual Average Daily Traffic (AADT)); and

n = Number of years of crash data .

(AASHTO 2010a)

The crash rate was then calculated by Equation (3.2):

$$R_i = \frac{N_{observed,i(total)}}{MEV_i} \tag{3.2}$$

Where:

R_i = Observed crash rate at intersection, i;

$N_{observed,i(total)}$ = Total observed crashes at intersection, i; and

MEV_i = Million entering vehicles at intersection, i.

(AASHTO 2010a)

The intersections were then ranked based on the Crash Rate calculated for each intersection.

Part of the critical crash rate method required a statistical constant, p-value, that represents the confidence level desired (AASHTO 2010a). The P Values associated with the specific confidence levels can be seen in Figure 3.3 which shows a table taken from Volume 1 of the Highway Safety Manual pp4-36.

Table 4-9. Confidence Levels and P Values for Use in Critical Rate Method

Confidence Level	P_c—Value
85 percent	1.036
90 percent	1.282
95 percent	1.645
99 percent	2.326
99.5 percent	2.576

Source: *Road Safety Manual*, PIARC Technical Committee on Road Safety, 2003, p. 113

Figure 3.3: Confidence Levels and P Values for Critical Rate Method (AASHTO 2010a)

The P value of 1.036 for 85 percent confidence level was selected through trial and error. A higher confidence limit only flagged a few intersections, whereas the 85 percent confidence level identified five roundabouts for further investigation.

Once the Crash Rate for each intersection was calculated in accordance with equations (3.1) and (3.2) the Weighted Average Crash Rate per Population was calculated as per Equation (3-3):

$$R_a = \frac{\sum_{i=1}(TEV_i \times R_i)}{\sum_{i=1}(TEV_i)} \qquad (3\text{-}3)$$

Where:

R_a = Weighted Average Crash Rate for reference population;

R_i = observed crash rate at site, i; and

TEV_i = Total Entering Vehicles per day for intersection, i.

(AASHTO 2010a)

The Critical Crash Rate was then calculated as per Equation (3-4):

$$R_{c,i} = R_a + \left[P \times \sqrt{\frac{R_a}{MEV_i}}\right] + \left[\frac{1}{2 \times (MEV_i)}\right] \qquad (3\text{-}4)$$

Where:

$R_{c,i}$ = Critical Crash Rate for intersection, i;

R_a = Weighted Average Crash Rate for reference population;

P = P value for corresponding confidence level; and

MEV_i = Million Entering Vehicles for intersection, i.

(AASHTO 2010a)

The intersections were then ranked based on their Crash Rate and any crash rates that exceeded the Critical Crash Rate were identified for further investigation (AASHTO 2010a).

3.3.2 Relative Severity Index Method

The Relative Severity Index (RSI) method uses societal crash costs based on the type of crash that are assigned to each crash at each site to develop a Relative Severity Index (RSI) (AASHTO 2010a). The average RSI cost for each intersection is compared with the average RSI cost for the respective population to determine which intersections exceed the average and to rank the intersections (AASHTO 2010a).

The RSI costs used for this method were based on those proposed by Andreassen in his report; Crash Costs – 2001: costs by accident-type (Andreassen 2001), factored up by CPI to 2016 dollars. Austroads Guide to Road Safety Part 8 also refers to the costs by crash type found in Andreassen's work (Austroads 2015a). The adopted costs are shown in Table 3.1.

Table 3.1: Costs by Crash Type

DCA code group	DCA codes	Description	Low Speed <80km/h $
Two vehicle crashes			
1	100–109	Intersection, from adjacent approaches	$95,193
2	201, 501	Head-on	$217,322
3	202–206	Opposing vehicles, turning	$94,217
4	301–303	Rear-end	$47,292
5	305–307, 504	Lane change	$73,862
6	308, 309	Parallel lanes, turning	$66,062
7	207, 304	U-turn	$90,317
8	401, 406–408	Entering roadway	$66,915
9	503, 505, 506	Overtaking, same direction	$89,464
10	402, 404, 601, 602, 604, 608	Hit parked vehicle	$67,037
11	903	Hit train	$264,126
Single vehicle crashes			
12	001–009	Pedestrian	$200,624
13	605	Permanent obstruction on carriageway	$91,292
14	609, 905	Hit animal	$49,120
15	502, 701, 702, 706, 707	Off carriageway, on straight	$73,862
16	703, 704, 708, 904	Off carriageway, on straight, hit object	$141,631
17	705	Out of control, on straight	$102,872
18	801, 802	Off carriageway, on curve	$125,176
19	803, 804	Off carriageway, on curve, hit object	$167,715
20	805, 806, 807	Out of control, on curve	$106,894
Exceptions			
21	000, 200, 300, 400, 500, 600, 700, 800, 900, 901, 906, 907, 403, 405, 606, 607, 610	Crashes which are unlikely to be attributable to any road environment factor, and which are therefore unlikely to be addressed by any road-based remedial treatment. Crashes in this DCA code group will not be used in crash rates.	
Table adapted from Austroads Guide to Road Safety Part 8 (Austroads 2015a)			

An average RSI cost was calculated for each intersection by summing the total RSI costs for the intersection, based on the crash frequency of each type of crash multiplied with the respective RSI cost, and dividing by the total number of crashes at the intersection, as per Equation (3.5):

$$\overline{RSI_i} = \frac{\sum_{j=1}^{n} RSI_j}{N_{observed,i}} \tag{3.5}$$

Where:

$\overline{RSI_i}$ = Average RSI cost for the intersection, i;

RSI_j = RSI cost for each crash type, j; and

$N_{observed,i}$ = Number of observed crashes at the site, i.

(AASHTO 2010a)

The average RSI cost for the respective population was calculated by Equation (3.6):

$$\overline{RSI_{av(control)}} = \frac{\sum_{i=1}^{n} RSI_i}{\sum_{i=1}^{n} N_{observed,i}} \tag{3.6}$$

Where:

$\overline{RSI_{av(control)}}$ = Average RSI cost for the reference population (control group);

RSI_i = Total RSI cost at site, i; and

$N_{observed,i}$ = number of observed crashes at site, i.

(AASHTO 2010a)

If the average RSI costs for a specific intersection exceeded the average RSI cost for the respective population it was flagged for investigation.

3.4 Ranking of Top 10 Roundabouts

Lists of the top ten roundabouts were identified both using the critical crash rate method and the RSI index method and each roundabout was given a score based on its crash rate and RSI cost compared with the total crash rates and RSI cots. Weighting factors were applied to the two methods to combine the results and form one list. These weighting factor were selected to be 0.5 applied to each method.

The two lists were compared and a combination of the two lists was adopted as the final top 10 worst performing roundabouts. These two lists were combined by applying weighting factors to the scores of the two different methods. The weighting factors were set at 0.5 for each method as the two methods considered quite different factors. The critical crash rate method considered crash frequency and traffic volume at each site but didn’t distinguish between types or severity of crashes whereas the RSI method considered crash type and the potential severity for each crash type but did not consider traffic volume for each site.

The adopted list was then used in the excess proportion of specific crash type method to identify whether there were roundabouts that presented with an excess of one of either angle, hit object or rear-end crashes.

3.5 Crash Investigations

The focus of this investigation was to identify geometric properties that may have contributed to the poor safety performance of the roundabouts.

The aim of the crash investigation was to identify crash contributory factors by investigating the crashes that have occurred at the roundabouts. Each roundabout was considered separately to identify clusters of crashes occurring at particular locations on the roundabout or a high number of a particular type of crash. Then once patterns or trends such as these were identified, possible contributory factors were considered.

Part of the crash investigation included applying one of the Highway Safety Manual methods the Excess Proportion of Specific Crash Type Exceeding Threshold method. This method identifies sites that have an excess of a particular type of crash so treatments can be targeted to reducing the severity and frequency of specific types of crashes.

3.5.1 Excess Proportion of Specific Crash Type Exceeding Threshold

The Excess Proportion of Specific Crash Type method uses the proportion of a particular type of crash at each intersection compared with a threshold proportion to determine which intersections exceed the threshold proportion to identify where a specific type of crash is overrepresented (AASHTO 2010a).

This method was used on the identified top 10 worst performing roundabouts to determine if any of these roundabouts had an excess proportion of a particular crash type (target crash type) in comparison to the other roundabouts. This was done for the three most common crash types at roundabouts in Toowoomba, Angle, Hit Object and Rear-end. The method for calculating the excess proportion is outlined below.

The observed proportion of the target collision type was calculated using Equation (3-7):

$$p_i = \frac{N_{observed,i}}{N_{observed,i(total)}} \tag{3-7}$$

Where:

p_i = Observed proportion at site i;

$N_{observed,i}$ = Number of observed target crashes at site i; and

$N_{observed,i(total)}$ = Total number of crashes at site i.

(AASHTO 2010a)

A threshold proportion of the target collision type under investigation was calculated using Equation (3-8):

$$p_i^* = \frac{\sum N_{observed,i}}{\sum N_{observed,i(total)}} \tag{3-8}$$

Where:

p_i^* = Threshold proportion;

$\sum N_{observed,i}$ = Sum of observed target crash frequency within population;

$\sum N_{observed,i(total)}$ = Sum of total observed crash frequency within population.

(AASHTO 2010a)

The sample variance (s^2) was calculated for each reference population using Equation (3-9):

$$Var(N) = \left(\frac{1}{n_{sites} - 1}\right) \times \left[\sum_{i=1}^{n} \left(\frac{\left(N_{observed,i}\right)^2 - N_{observed,i}}{\left(N_{observed,i(total)}\right)^2 - N_{oberseved,i(total)}}\right) - \left(\frac{1}{n_{sites}}\right) \times \left(\sum_{i=1}^{n} \frac{N_{observed,i}}{N_{observed,i(total)}}\right)^2\right] \quad (3\text{-}9)$$

for $N_{observed,i(total)} \geq 2$

Where:

n_{sites} = Total number of sites analysed;

$N_{observed,i}$ = Observed target crashes for a site i; and

$N_{observed,i(total)}$ = Total number of crashes for a site i.

(AASHTO 2010a)

The sample mean proportion of target crashes was calculated using Equation (3-10).

$$\overline{p_i^*} = \frac{\sum p_i}{n_{sites}}, N_{observed,i} \geq 2 \quad (3\text{-}10)$$

Where:

n_{sites} = Total number of sites analysed;

$\overline{p_i^*}$ = Mean proportion of target crash types; and

p_i = Observed proportion.

(AASHTO 2010a)

The Alpha and Beta parameters for each reference population were calculated using Equations (3-11) and (3-12) from the Highway Safety Manual (AASHTO 2010a).

$$\alpha = \frac{\left(\overline{p_i^*}^2 - \overline{p_i^*}^3 - s^2\overline{p_i^*}\right)}{Var(N)} \quad (3\text{-}11)$$

$$\beta = \frac{\alpha}{\overline{p_i^*}} - \alpha \quad (3\text{-}12)$$

Where:

$Var(N)$ = Variance (equivalent to the square of the standard deviation, s^2); and

$\overline{p_i^*}$ = Mean proportion of target crash types.

Finally, the probability for the particular crash type at each intersection was calculated using Equation (3-13). This equation required the use of a beta distribution function such as that in Microsoft Excel.

$$p\left(\frac{p_i > p_i^*}{N_{observed,i}, N_{observed,i(total)}}\right) = 1 - betadist\left(p_i^*, \alpha + N_{observed,i(total)} - N_{observed,i}\right) \quad (3\text{-}13)$$

Where:

p_i^* = Threshold proportion;

p_i = Observed proportion;

$N_{observed,i}$ = Observed target crashes for a site i; and

$N_{observed,i(total)}$ = Total number of crashes for a site i.

(AASHTO 2010a)

The intersections were then ranked based on the probability values that are interpreted as: *the probability that the long-term expected proportion of a particular type of crash at a particular intersection is greater than the long-term expected proportion of all intersections in the reference population*. A high probability would suggest further investigation of that particular type or severity of crash would be beneficial.

Once the probability of exceeding the proportion threshold was calculated a limiting probability was selected. This selection depended on the distribution of values and how many sites were to be investigated.

The excess proportion was calculated, which was simply the difference between the true observed proportion and the threshold proportion for each site using Equation (3-14):

$$p_{diff} = p_i - p_i^* \quad (3\text{-}14)$$

Where:

p_i^* = Threshold proportion; and

p_i = Observed proportion.

(AASHTO 2010a)

The sites were then ranked in descending order based on the value of the excess proportion (p_{diff}). If a large difference was identified between the observed proportion and the threshold proportion, then it is likely that countermeasures targeted at that specific crash type will improve the crash rate (AASHTO 2010b).

3.6 Road Safety Audits

The aim of the road safety audit was a proactive process to identify road features or geometry that could potentially be a contributory factor to crashes. Austroads have a set of guidelines on how to conduct a road safety audit on intersections. Once the top ten (10) worst performing roundabouts were identified and ranked a road safety audit was conducted at each of the roundabouts to identify aspects of the intersections that could be improved to increase the safety of the roundabouts.

The road safety audit included site visits to each of the roundabouts to identify likely contributing factors. The site visits were conducted by three people of varying road safety awareness and training. A limitation of these audits was they were not conducted by a qualified road safety auditor as recommended in Austroads, however, for the purposes of the investigation the experience of the three people was considered appropriate. The site visits were conducted by first driving each approach to understand the driver experience and identify any potential issues approaching the intersections in a car. The site investigation included walking around each leg of the roundabout checking for potential issues on both the carriageway and the footpath and photos were taken of any identified issues. Each leg was crossed as a pedestrian and the experience was documented including things such as sight distance and traffic volumes. Part of these site visits was also to observe the behaviour of the road users as their behaviour can indicate features that are affecting the safety performance of the roundabouts.

The Austroads Guidelines provide checklists to assist in the road safety audit. As advised in the Austroads publication, these checklists were used both on the computer using aerial images, drawings and data as well as at the site inspection and when writing up the report (Austroads 2009b). The checklist used for the road safety audits was adapted from Austroads Guide to Road Safety Part 6, ‘Checklist 6: Existing Roads’ (Austroads 2009b). The checklist used for the road safety audits is included in Appendix B.

Part of the road safety audit also included the investigation of geometric features that may affect the crash rates. These geometric features were measured using Google Earth Pro. It is important to note that due to the use of satellite imagery to measure these geometric properties there are significant limitations in regard to accuracy.

3.7 Propose remedial measures

Once the worst performing roundabouts were identified and investigated remedial treatments were proposed to improve the performance of the roundabouts by addressing the contributory factors identified in the road safety audits and crash investigations.

4.0. RESULTS AND DISCUSSION

4.1 Preliminary Data Analysis

The preliminary data analysis was conducted for a 5 year period of crash data from 2006 to 2010 at all of the roundabouts in Toowoomba with the aim of identifying trends of roundabout crashes throughout Toowoomba.

The number of crashes at roundabouts per year is presented in Figure 4.1. This shows a gradual increase in crashes from 2006 to 2009, however there is a significant reduction in crashes at roundabouts in Toowoomba in 2010. The steady increase of crashes each year is likely attributed to an increase in traffic volume as a result of population growth in the region. The exact cause of the reduction in the number of crashes in 2010 is unknown but without more recent data is not appropriate to assume this will continue. The proportions of crashes in each crash severity category remain similar each year.

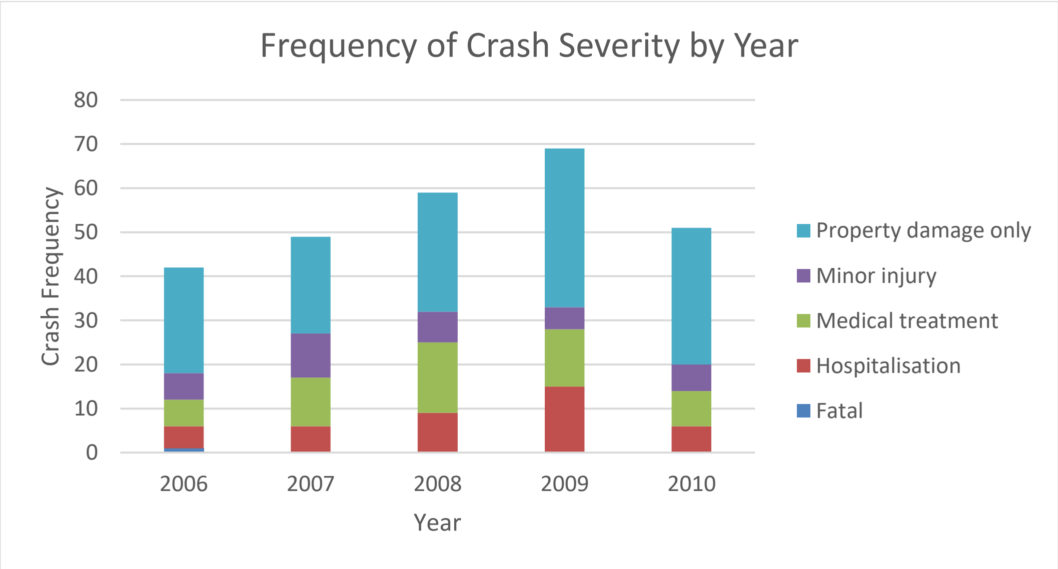


Figure 4.1: Frequency of crash severity by year at roundabouts in Toowoomba

Figure 4.2 presents the overall crash severity frequency and distribution for the five severity categories at all of the roundabouts in Toowoomba. As can be seen in Figure 4.2, there is only one fatality in the five year period. This is supported by the literature as roundabouts are one of the best intersection types for reducing the severity of crashes. The most common severity level seen at Toowoomba roundabouts is ‘Property Damage Only’ with 52% of crashes falling into this category.

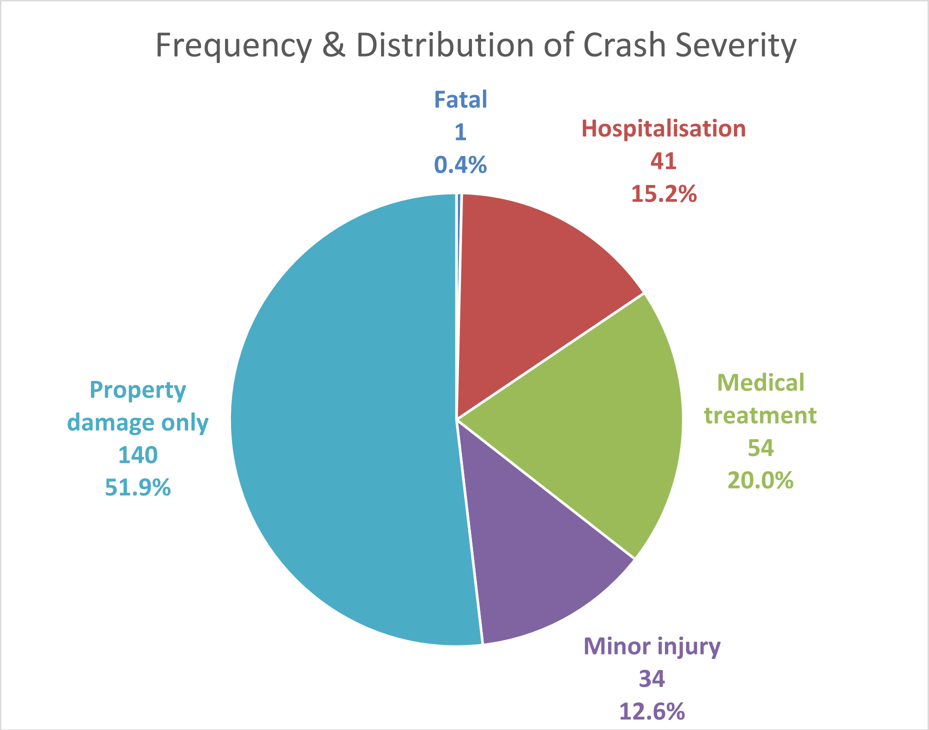


Figure 4.2: Frequency and distribution of crash severity at roundabouts in Toowoomba

The frequency of crash types is indicated in Figure 4.3 which shows that the majority of crashes in Toowoomba are multiple vehicle crashes (85%), followed by single vehicle crashes (15%) and very few hit pedestrian crashes.

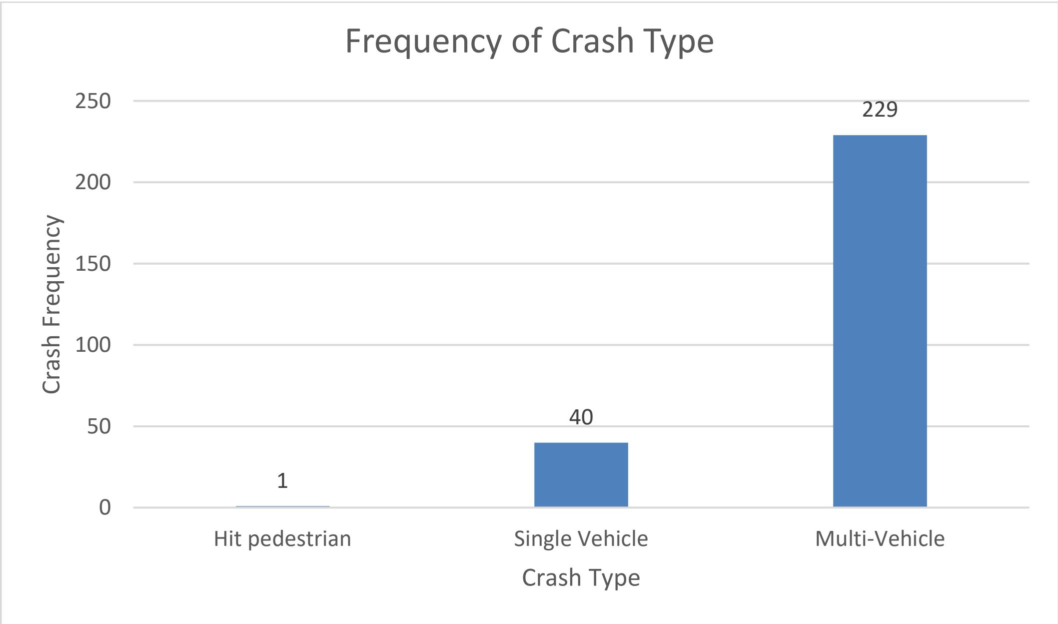


Figure 4.3: Frequency of crash types at Toowoomba roundabouts

The frequency and distribution of crash types at roundabouts in Toowoomba are presented in Figure 4.4. It is clear that the majority of road crashes (74%) are ‘Angle’ crashes which is supported by literature as the main type of road crash at roundabouts. The other two crash types that have any significant number include ‘Hit object’ and ‘Rear-end’ which are 12.6% and 8.9% respectively. All of the other crash types contribute less than 5% combined.

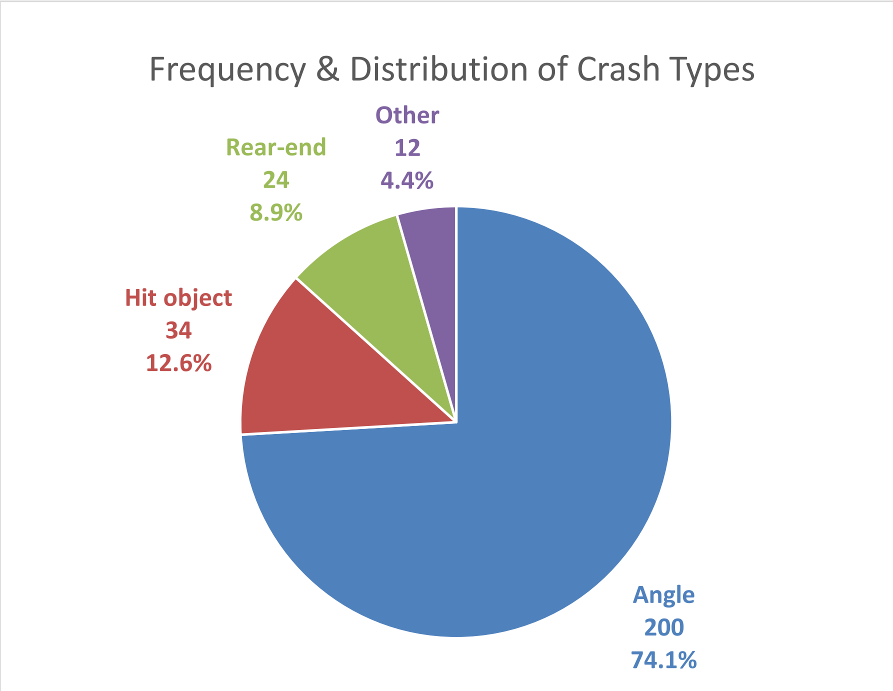


Figure 4.4: Frequency and distribution of crash types at Toowoomba Roundabouts

The road user frequency and distribution involved in crashes at roundabouts in Toowoomba are shown in Figure 4.5. As expected, cars are the most common road user involved in road crashes at roundabouts in Toowoomba. Bicycles and motorcycles are the next most common road user involved in road crashes with each of these road users representing approximately 5% of crashes. Trucks are involved in approximately 4% of crashes and the remaining road users: bus, pedestrian and other account for less than 1% of road crashes at roundabouts in Toowoomba.

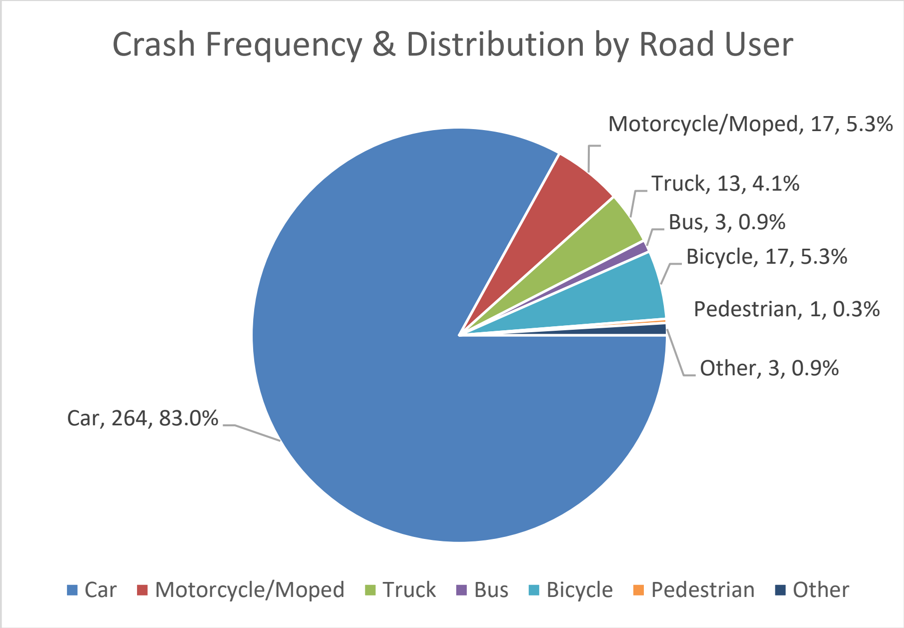


Figure 4.5: Crash frequency and distribution by road user at roundabouts in Toowoomba

The frequency of crashes per month is presented in Figure 4.6. The Winter months, July and August, have the highest crash frequency. This is likely due to the weather conditions in winter when there are many mornings and evenings with heavy fog, affecting road users' sight distance and reaction time. It is also likely that due to Toowoomba's weather conditions more people would be opting to drive their car rather than walking, therefore resulting in more vehicles on the roads during these winter months. The months with the lowest crash frequency are January, March and September. These three months line up closely with the Queensland school holiday periods which would significantly decrease the traffic volumes at peak times throughout the day.

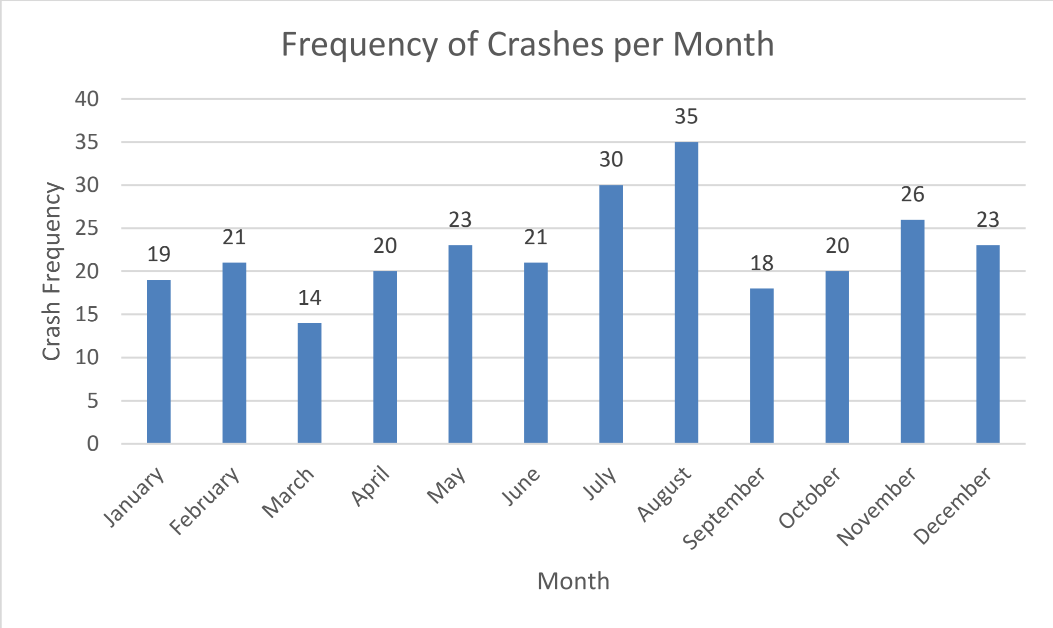


Figure 4.6: Frequency of crashes by month at roundabouts in Toowoomba

The distribution of crashes per day are presented in Figure 4.7. It is clear that weekends have the lowest frequency of crashes. This is mainly due to the reduction in traffic volume during peak hours – each person has different routines on weekends which spreads the traffic out over the day. The highest frequency of crashes occurs on a Friday. This is likely to be the result of driver behaviour rather than the road environment. Drivers are less attentive to the driving task and more fatigued by Friday causing driver mistakes that can lead to crashes.

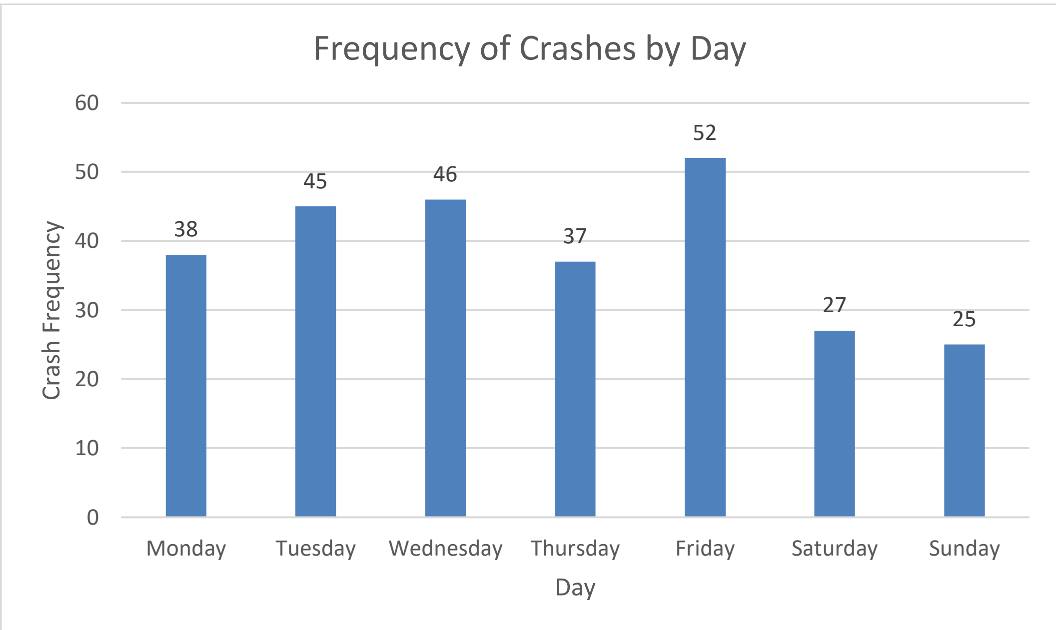


Figure 4.7: Frequency of crashes by day at roundabouts in Toowoomba

Figure 4.8, depicting an hourly crash distribution, indicates a distinct pattern much like that of traffic volumes throughout the day. The two most distinctive peaks are at 8am and 3pm with the next highest frequency at 5pm. These times correspond to peak hour traffic where road users are travelling to and from work and school. It is also important to note that there is a higher frequency of road crashes in the afternoon/evening as the road user is more fatigued and less alert.

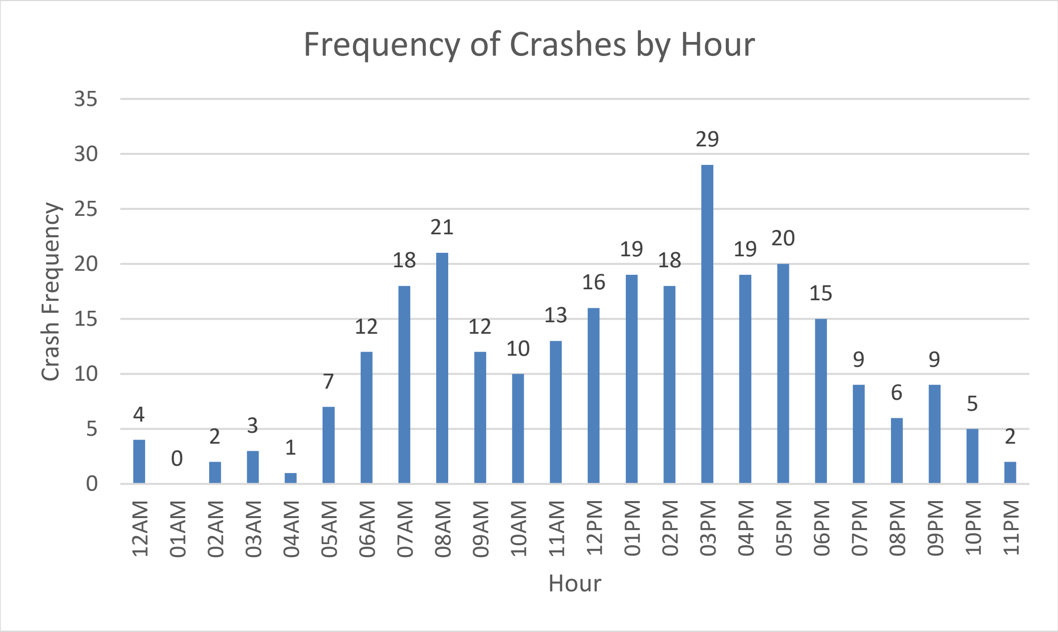


Figure 4.8: Frequency of crashes by hour at roundabouts in Toowoomba

4.2 Road Safety Methodologies for Ranking Roundabouts

As discussed in the Methodology, only the roundabouts with 5 or more crashes were considered in the critical crash rate and RSI methods to develop a ranking of the roundabouts to reduce the impact that roundabouts with low crash numbers had on the methods. As such 16 roundabouts were considered in the ranking methods.

4.2.1 Critical Crash Rate Method

A crash rate was calculated for each of the 16 roundabouts based on the number of crashes at each site as well as the traffic volume. From these crash rates a weighted average crash rate, R_a, was calculated which represented the average crash rate for the 16 roundabouts. This was then used to calculate critical crash rates for each of the sites.

Roundabouts that had a higher observed crash rate than critical crash rate, $R_i > R_{ci}$, were flagged for further investigation, as per volume 1 of the Highway Safety Manual (AASHTO 2010a). The weighted average crash rate value was calculated to be 0.244 which flagged three roundabouts to be investigated further; NW6, SW6 and SW7. However, because the aim of the investigation was to identify the top ten roundabouts, this threshold value was adjusted until ten roundabouts were flagged. This resulted in a weighted average crash rate of 0.144. Each of the roundabouts were assigned a score to be used when combining the two methods together. The score was calculated using Equation (4-1):

$$Score = \frac{Crash\ Rate}{\sum Crash\ Rates} \times 100 \tag{4-1}$$

The roundabouts are shown ranked from 1 to 16 in Table 4.1.

Table 4.1: Critical Crash Rate Method Ranking

Rank		Roundabout	$N_{observed}$	Crash Rate	Critical Crash Rate		Score
1	SW7	Glenvale Rd & McDougall St	12	0.424	0.235	🚩	10.96
2	NW6	Anzac Ave, Russell St & West St	27	0.394	0.199	🚩	10.16
3	SW6	Glenvale Rd & Greenwattle St	16	0.372	0.215	🚩	9.61
4	SE21	Spring St & Hume St	10	0.265	0.221	🚩	6.84
5	SE12	South St & MacKenzie St	9	0.247	0.223	🚩	6.38
6	SE13	Alderley St & Hume St	15	0.246	0.202	🚩	6.36
7	NW7	North St & Tor St	9	0.230	0.219	🚩	5.95
8	SE14	Alderley St & Ramsay St	11	0.230	0.211	🚩	5.93
9	SE15	Alderley St & MacKenzie St	9	0.219	0.217	🚩	5.66
10	SE5	Long St & Hume St	11	0.212	0.208	🚩	5.47
11	NW1	Heinemann Rd, Troys Rd, Toowoomba-Cecil Plains Rd & Carrington Rd	5	0.223	0.249		5.75
12	SW1	Alderley St & Drayton Rd	11	0.195	0.205		5.03
13	SE8	Long St & MacKenzie St	8	0.189	0.216		4.88
14	NW3	Hursley Rd & McDougall St	6	0.158	0.221		4.09
15	SE10	South St & Hume St	6	0.157	0.220		4.05
16	SE19	Stenner St & Ramsay St	5	0.111	0.214		2.88

Sites were flagged for further investigation. $\boldsymbol{R_i > R_{ci}}$

4.2.2 Relative Severity Index Method

A limitation that was identified with this particular method was that there was no ability to distinguish between road users involved in a crash. This was causing incorrect ranking particularly for sites that had several crashes where bicycle and motorbike road users were involved. For instance, some roundabouts had a clear excess of bicycle crashes, however they were not being ranked any higher even though the severity for a bicycle or motorbike road user is considerably higher. To reduce the impact this limitation had on the final ranking of the roundabouts, factors were applied to crashes which involved bicycle or motorbike road users to provide a more accurate representation of the social cost of these crashes. To determine these factors, the full data for the 49 roundabouts was analysed to determine the distribution of crash severity for different road users as depicted in Figure 4.9.

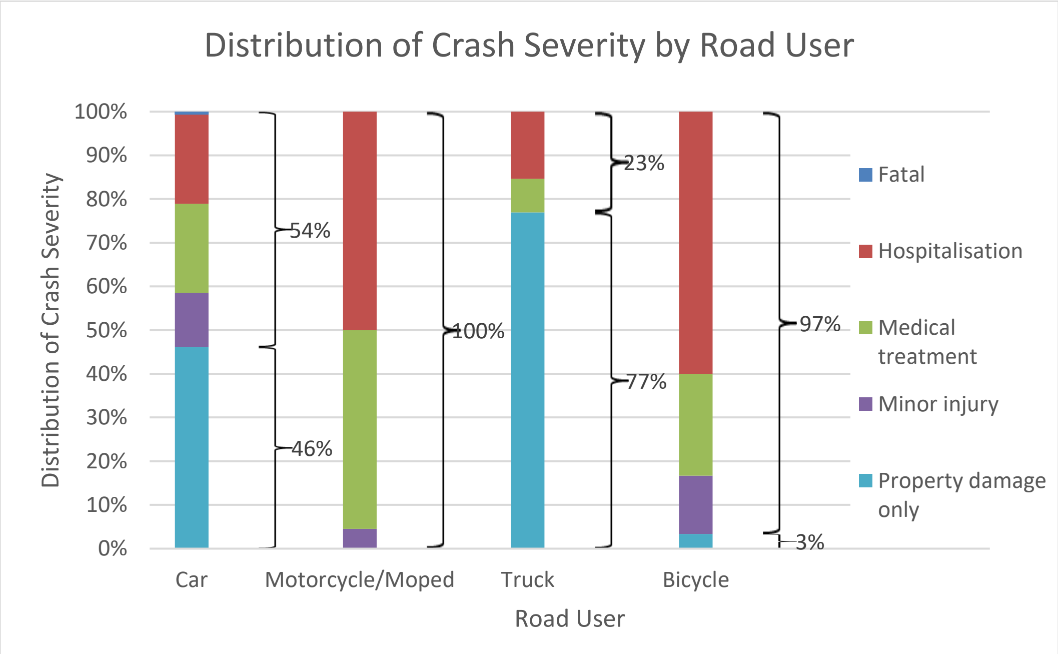


Figure 4.9: Distribution of crash severity by road user at roundabouts in Toowoomba – brackets show the proportions of property damage only crashes and crashes resulting in injury.

From this data the proportions of injury and non-injury crashes for different road users were determined. As can be seen in Figure 4.9 above, property damage only crashes made up 46% and 77% of car and truck crashes respectively which indicated crashes involving these road users were less likely to result in injury. Motorcycle and bicycle users however had a much higher rate of injury at 100% and 97% respectively. This was such a drastic difference in distribution of crash severity re-enforcing the need to consider what road users are involved for the costing of a road crash type. From these results it was decided to apply a weighting factor to crashes involving motorcycle and bicycle road users. These factors were selected by identifying percentage increase in injury crashes for motorcycle and bicycle road users; i.e.:

$motorcycle\ \%\ injury - car\ \%\ injury = 100\% - 54\% = 46\%$; and

$$bicycle\ \%\ injury - car\ \%\ injury = 97\% - 54\% = 43\%$$

Thus the weighting factors were selected to be 1.46 for motorcycle road users and 1.43 for bicycle road users which were applied to the crash type cost for the relative severity index costs for each crash type. These factors are essentially representing that injury crashes are 46% more likely to result in an injury crash if a motorcycle is involved compared to a car, so the cost for a crash type involving a motorcyclist should also be 46% higher

Costs were assigned to each crash at each of the 16 roundabouts considered in the ranking method based on crash type in accordance with Table 3.1. An average RSI cost was calculated for each intersection as well as an average RSI costs for the reference population which consisted of all 16 roundabouts. The two average costs were compared and if a site was identified as having a higher average RSI cost per crash than the population average it was flagged for further investigation. The reference population average RSI was calculated to be $101,641.

Each of the roundabouts were assigned a score to be used when combining the two methods together. The score was calculated using Equation (4-2).

$$Score = \frac{RSI\ Cost}{\sum RSI\ Costs} \times 100 \tag{4-2}$$

The resulting ranking of the roundabouts using the RSI method are shown in Table 4.2.

Table 4.2: RSI Method Ranking

Rank		Roundabout	$N_{observed}$	Average RSI cost		Score
1	NW7	North St and Tor St	9	$116,480	🚩	7.22
2	SW1	Alderley St and Drayton Rd	10	$112,509	🚩	6.98
3	SE8	Long St and MacKenzie St	8	$110,448	🚩	6.85
4	SW6	Glenvale Rd and Greenwattle St	16	$105,783	🚩	6.56
5	SE14	Alderley St and Ramsay St	11	$103,636	🚩	6.43
6	NW6	Anzac Ave, Russell St and West St	26	$103,400	🚩	6.41
7	SE19	Stenner St and Ramsay St	5	$103,380	🚩	6.41
8	SE15	Alderley St and MacKenzie St	9	$102,741	🚩	6.37
9	NW3	Hursley Rd and McDougall St	6	$102,015	🚩	6.33
10	SE21	Spring St and Hume St	10	$100,461		6.23
11	SW7	Glenvale Rd and McDougall St	12	$98,842		6.13
12	SE12	South St and MacKenzie St	9	$95,193		5.90
13	SE13	Alderley St and Hume St	15	$94,429		5.86
14	SE5	Long St and Hume St	11	$93,964		5.83
15	SE10	South St and Hume St	5	$85,613		5.31
16	NW1	Heinemann Rd, Troys Rd, Toowoomba-Cecil Plains Rd and Carrington Rd	5	$83,394		5.17

🚩 **Cells flagged for further investigation.** $RSI_i > RSI_{Av(control)}$

4.3 Top 10 Worst Performing Roundabouts

To generate a list of the top ten roundabouts from the two road safety methodologies; Critical crash rate and RSI method it was decided to combine the methods using weightings for the two different methods to develop a final top ten ranking. This was done because the two methods considered different factors and all are significant when considering what sites need to be improved. The critical crash rate method considers crash frequency in relation to the traffic volume at each site and identifies sites that exceed a critical limit. Whereas the RSI method considers societal costs for different DCA crash types which incorporate the potential severity of each type of crash. A higher weighting was also applied to crashes that involved a motorcycle or bicycle road user as the chances of injury was significantly higher in these crash types. It was not considered appropriate to only use one of these methods and a combination of the two methods was considered by applying a weighting factor of 0.5 to the score of the crash rate method and the RSI method which was selected based on a sensitivity analysis discussed in the next section.

The resulting ranking is shown in Table 4.3.

Table 4.3: Final ranking of top 10 worst performing roundabouts in Toowoomba

		Roundabouts	**Crash Rate Method**	**RSI Method**	**Combined Score**
1	SW7	Glenvale Road and McDougall Street	10.96	6.13	8.55
2	NW6	Anzac Avenue, Russell Street and West Street	10.16	6.41	8.29
3	SW6	Glenvale Road and Greenwattle Street	9.61	6.56	8.09
4	NW7	North Street and Tor Street	5.95	7.22	6.59
5	SE21	Spring Street and Hume Street	6.84	6.23	6.53
6	SE14	Alderley Street and Ramsay Street	5.93	6.43	6.18
7	SE12	South Street and MacKenzie Street	6.38	5.90	6.14
8	SE13	Alderley Street and Hume Street	6.36	5.86	6.11
9	SE15	Alderley Street and MacKenzie Street	5.66	6.37	6.02
10	SW1	Alderley Street and Drayton Road	5.03	6.98	6.00
	SE8	Long Street and MacKenzie Street	4.88	6.85	5.87
	SE5	Long Street and Hume Street	5.47	5.83	5.65
	NW1	Heinemann Road, Troys Road, Toowoomba-Cecil Plains Road and Carrington Road	5.75	5.17	5.46
	NW3	Hursley Road and McDougall Street	4.09	6.33	5.21
	SE10	South Street and Hume Street	4.05	5.31	4.68
	SE19	Stenner Street and Ramsay Street	2.88	6.41	4.64

A sensitivity analysis was conducted to identify how much the weighting factors changed the final ranking and the results are provided in Table 4.4. The weighting factors are shown from 30 to 70% as any weighting factors lower or higher than this weren’t going to be considered.

Table 4.4: Sensitivity analysis for ranking method weighting factors

	Roundabout	Combined Score (50/50)	Ranking				
			70/30	60/40	50/50	40/60	30/70
SW7	Glenvale Rd & McDougall St	8.55	1	1	1	1	1
NW6	Anzac Ave, Russell St & West St	8.29	2	2	2	2	2
SW6	Glenvale Rd & Greenwattle St	8.09	3	3	3	3	3
NW7	North St & Tor St	6.59	5	5	4	4	4
SE21	Spring St & Hume St	6.53	4	4	5	5	5
SE14	Alderley St & Ramsay St	6.18	8	8	6	6	7
SE12	South St & Mackenzie St	6.14	6	6	7	8	10
SE13	Alderley St & Hume St	6.11	7	7	8	11	11
SE15	Alderley St & Mackenzie St	6.02	9	9	9	9	9
SW1	Alderley St & Drayton Rd	6.00	10	10	10	7	6
SE8	Long St & Mackenzie St	5.87	13	11	11	10	8
SE5	Long St & Hume St	5.65	11	12	12	12	12
NW1	Heinemann Rd, Troys Rd, Toowoomba-Cecil Plains Rd & Carrington Rd	5.46	12	13	13	14	15
NW3	Hursley Rd & McDougall St	5.21	14	14	14	13	13
SE10	South St & Hume St	4.68	15	15	15	16	16
SE19	Stenner St & Ramsay St	4.64	16	16	16	15	14

From this table it can be seen that there are distinct blocks shown by the different colours that the roundabouts scores fit into. The first block, shown in blue, demonstrates that the roundabouts SW7, NW6 and SW6 all remain as the top 3 roundabouts in the same order regardless of which weighting factors are used all with combined scores above 8. The second block, shown in green, demonstrates that the roundabouts NW7 and SE21 remain as rank 4 or 5 regardless of which weighting factors are applied only the order swaps and they both of scores around 6.5. The third and fourth blocks, shown in purple and orange respectively, were not as distinguishable. These blocks were separated by including any roundabout that had a rank 6-10 in the third block and 11-16 in the fourth block. This reflects quite well in the combined scores for these blocks where block 3 had combined scores between 5.87 to 6.18 and block 4 between 4.64 to 5.65. This table demonstrates that only really the top 5 roundabouts are confidently ranked. The roundabouts from rank 6 onwards change quite significantly depending on which method is used and this is due to their scores being so similar to each other. This is also an indication that they are similar in performance.

4.4 Crash Investigations and Road Safety Audits

Some potential crash contributory factors have been identified through crash investigations and road safety audits at each of the top 10 roundabouts in Toowoomba.

Road safety audits were undertaken on Sunday 11 September 2016 at each of the top 10 ranked roundabouts. The results from these road safety audits as well as the crash investigations are presented in the following sections for each of the top 10 roundabouts. The full list of findings and associated photos from the road safety audit site investigations are included in Appendix F.

As part of the road safety audits the geometric features of each roundabout were measured using Google Earth Pro to identify particular geometric features that do not meet the recommended design requirements. A table outlining the recommended design requirements is shown in Table 4.5 and is used to identify features that do not meet the requirements using colours as defined in this table.

Table 4.5: Recommended design parameters for roundabout geometry

	Recommended Design Parameters	
Centre Island Diameter (m)	Minimum: 10m Desirable: 12m (Austroads 2015b)	< 10m – red 10 – 12m – green > 12m – orange
Circulating Roadway Width (m)	Table 4.3 from Austroads Guide to Road Design Part 4B: Roundabouts p32, (Austroads 2015b)	
Weaving Width (m)	Larger weaving width, poorer performance, (Anjana 2015)	
Weaving Length (m)	Larger weaving length, poorer performance, (Anjana 2015)	
Approach Width (m)	Minimum 3.0m	
Entry Width (m)	Desirable: ≥5m (to allow traffic to pass disabled vehicle General range: 3.4 – 4.0 m (Department of Transport and Main Roads 2006)	< 3.4m – red 3.4-4m – green > 4m – amber
Exit Width (m)	Minimum 3.0m	
Eccentricity (m)	0m	
Angle to Next Leg (degrees)	90° (Austroads 2015b)	< 90° – amber = 90° – green > 90° – red
Deflection Radius (m)	Maximum: 100m (Arndt 2008)	< 70m – green 70-100m – amber > 100m – red
Approach Gradient (%)	Recommended limit: 3-4%, Max: 6% (Austroads 2015b)	< 4% – green 4-6% – amber >6% – red
Entry Path Radius (m)	Maximum radius of 55m 1.6 x actual entry path radius (two-lane entry cutting across lanes) (Austroads 2015b)	<55m - green 55-70 m - amber >70m - red

4.4.1 Excess Proportion of Specific Crash Type Exceeding Threshold

The excess proportion of specific crash type exceeding threshold method identified sites that had an excess of angle, hit object or rear-end crashes compared with the other roundabouts within the top 10. As is explained in the Highway Safety Manual, the resulting probability values are to be interpreted as the percent chance that the expected proportion of a specific crash type at the site is actually greater than the long term expected proportion for the reference population.

The probability values for excess proportion of angle crashes for the top ten roundabouts are shown in Table 4.6. Several of the roundabouts, SW6, SW7 and SE12 have only had angle crashes during the study period and so a very high probability was calculated for these roundabouts. All of the crashes except one crash was an angle crash at NW7 and SE21 which also resulted in a high probability value. SE14 and SE15 had probabilities around 50% which indicated they most likely had an excess but not confidently.

Table 4.6: Excess proportion of angle crashes at the top 10 roundabouts

		Roundabout	**Angle Crashes**	**Total Crashes**	**Probability**
1	SW7	Glenvale Road and McDougall Street	12	12	**0.988**
2	NW6	Anzac Avenue, Russell Street and West Street	19	27	0.263
3	SW6	Glenvale Road and Greenwattle Street	16	16	**0.996**
4	NW7	North Street and Tor Street	8	9	**0.838**
5	SE21	Spring Street and Hume Street	9	10	**0.869**
6	SE14	Alderley Street and Ramsay Street	8	11	0.446
7	SE12	South Street and MacKenzie Street	9	9	**0.973**
8	SE13	Alderley Street and Hume Street	7	15	0.013
9	SE15	Alderley Street and MacKenzie Street	7	9	0.589
10	SW1	Alderley Street and Drayton Road	4	11	0.007

The probability values for excess proportion of hit object crashes for the top 10 roundabouts are presented in Table 4.7. There were two sites that stood out in this table with probabilities of 84.1% and 90.9% for NW6 and SE14 respectively. Hit object crashes are usually quite rare and can be quite severe so it is important to highlight when there have been several.

Table 4.7: Excess proportion of hit object crashes at the top 10 roundabouts

		Roundabout	Hit Object Crashes	Total Crashes	Probability
1	SW7	Glenvale Road and McDougall Street	0	12	0.108
2	NW6	Anzac Avenue, Russell Street and West Street	4	27	**0.841**
3	SW6	Glenvale Road and Greenwattle Street	0	16	0.078
4	NW7	North Street and Tor Street	0	9	0.138
5	SE21	Spring Street and Hume Street	0	10	0.127
6	SE14	Alderley Street and Ramsay Street	3	11	**0.909**
7	SE12	South Street and MacKenzie Street	0	9	0.138
8	SE13	Alderley Street and Hume Street	1	15	0.353
9	SE15	Alderley Street and MacKenzie Street	0	9	0.138
10	SW1	Alderley Street and Drayton Road	1	11	0.437

The probability values for excess proportion of rear-end crashes for the top ten roundabouts in Toowoomba are shown in Table 4.8. Roundabouts SE13, SW1 and SE15 were all calculated to have a high probability of having excess rear-end crashes with probabilities of 96.1%, 92.7% and 81.5% respectively.

Table 4.8: Excess proportion of rear-end crashes at the top 10 roundabouts

		Roundabout	Rear-end Crashes	Total Crashes	Probability
1	SW7	Glenvale Road and McDougall Street	0	12	0.108
2	NW6	Anzac Avenue, Russell Street and West Street	1	27	0.168
3	SW6	Glenvale Road and Greenwattle Street	0	16	0.075
4	NW7	North Street and Tor Street	0	9	0.145
5	SE21	Spring Street and Hume Street	0	10	0.131
6	SE14	Alderley Street and Ramsay Street	0	11	0.119
7	SE12	South Street and MacKenzie Street	0	9	0.145
8	SE13	Alderley Street and Hume Street	4	15	**0.961**
9	SE15	Alderley Street and MacKenzie Street	2	9	**0.815**
10	SW1	Alderley Street and Drayton Road	3	11	**0.927**

4.4.2 Rank 1: SW7 – Glenvale Road and McDougall Street

The worst performing roundabout identified was SW7 – Glenvale Road and McDougall Street.

SW7 Crash Investigation

An aerial photo of SW7 is shown in Figure 4.10. The crashes during the study period are shown by the coloured pins.

Figure 4.10: SW7 - Glenvale Road and McDougall Street roundabout crash diagram (Google Earth 2016)

There was a total of twelve crashes recorded at SW7 during the study period which were all multiple vehicle, angle crashes. This roundabout had the lowest traffic volume out of the top 10 roundabouts and yet had the fourth highest number of crashes which resulted in the highest calculated crash rate. The traffic volume proportions between the legs were

distributed relatively evenly across the north, east and west legs at approximately 28% on each leg, however, the southern leg had significantly less traffic with only 16%.
The 12 crashes that were recorded at this roundabout were all multiple vehicle, angle crashes that fell into the DCA group ‘Intersection from adjacent approaches’ with DCA code 101 except for one crash which was DCA code 104. The environmental conditions for all of the crashes were dry, clear conditions with nine of the crashes occurring during daylight and three at dawn/dusk.

This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess angle crashes compared to the other top 10 roundabouts.

The crash severity distribution included; 8 property damage only, 2 minor injury, 1 medical treatment and 1 hospitalisation. The medical treatment crash as the result of a crash between a car and a motorcycle and the remaining crashes were all between two cars.

SW7 Road safety audit

The key findings from the road safety audits include:

- Vehicles appeared to enter the roundabout at relatively high speed;
- Yellow ‘shared zone’ bicycle markings were present on the east and west legs (Glenvale Road) as well as signage – some of the bicycle symbols were faded, Figure F.3;
- The sight distance for the north and west approaches was considered excessive due to vacant land on the north-west and south-west corners, Figure 4.10 above. The excessive sight distance allows the road user to see well ahead what traffic is approaching the roundabout resulting in higher entry speeds if their path is clear. This causes a disadvantage to other approaches on the roundabout which have reduced sight distance as the vehicles are entering at higher speeds;
- Visibility on south leg was considered to be below average due to presence of low vegetation on south-east and south-west corners which obstructed the view of approaching vehicles due to the uphill grade of the approach, refer Figure F.4, Figure F.5 and Figure F.6; and
- At three of the pedestrian crossings the user must look around an electricity or light pole that is immediately next to the waiting area and on the east leg there is

a crest in the road that could obstruct fast travelling vehicles from the pedestrian, Figure F.7 and Figure F.8.

The geometric properties of this roundabout are summarised in Table 4.9.

Table 4.9: Geometric properties of SW7 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	14			
Circulating Roadway Width (m)	7.5	7.5	7.2	7.6
Single unit truck (6.9m); Semi (8.7m) (2m trafficable apron)	Adequate for a single unit truck and semi-trailer			
Weaving Width (m)	7.2	7.4	7.2	7.2
Weaving Length (m)	16.4	15.8	16.1	15.7
Approach Width (m)	3	5	4	3.8
Entry Width (m)	3.4	3.7	4.4	4.5
Exit Width (m)	4.5	4.3	5.2	4.8
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	50	75	80	75
Approach Gradient (%)	-4.5	4.1	1.6	-0.7
Entry Path Radius (m)	65	65	75	85

4.4.3 Rank 2: NW6 – Anzac Avenue, Russell Street and West Street

NW6 was identified as the second worst performing roundabout in Toowoomba. NW6 is one of only two roundabouts in Toowoomba that incorporate two lanes. The roundabout is a five leg roundabout and has two lane approaches on all of the legs except the north-west leg.

NW6 Crash Investigation

An aerial photo of NW6 is shown in Figure 4.11. The crashes during the study period are shown by the coloured pins.

Figure 4.11: NW6 - Anzac Avenue, Russell Street and West Street roundabout crash diagram (Google Earth 2016)

There was a total of 27 crashes recorded at NW7 roundabout throughout the study period. Of these 27 crashes, 15 resulted in property damage only, 3 resulted in minor injury, 4 resulted in medical treatment and 5 resulted in hospitalisation. There were 3 single vehicle crashes over the study period and 24 multiple vehicle crashes. Overall, the environment conditions were all dry, clear conditions except for 3 crashes which had wet, raining conditions. 20 of the crashes occurred during daylight, 1 at dawn/dusk and 5 during darkness (lighted). There were 13 crashes involving two cars, 3 crashes involving single cars, 2 crashes involving three cars, 3 crashes involving a bicycle and car, 4 crashes involving a truck and car, 1 crash involving a bus and car; and 1 crash involving two cars and a motorcycle.

The crashes have been summarised in Table 4.10 based on their DCA coding and environmental conditions.

Table 4.10: Crash Summary for NW6 roundabout

SINGLE VEHICLE CRASHES				
DCA Group	**DCA code**	**Total**	**Road User**	**Conditions**
Off carriageway on curve hit object	**803**	1	Car	Dry, clear, dawn/dusk
Off carriageway on straight hit object	**703**	1	Car	Wet, raining, daylight
	708	1	Car	Wet, raining, darkness (lighted)
MULTIPLE VEHICLE CRASHES				
DCA Group	**DCA code**	**Total**	**Road Users**	**Conditions**
Intersection from adjacent approaches	**100**	4	Car/car – 2 Bicycle/car – 1 Truck/car – 1	Dry, clear, daylight – 4
	101	8	Car/car – 6 Motorcycle/car – 1 Bus/car – 1	Dry, clear, daylight – 4 Darkness (lighted) – 3 Raining – 1
	102	1	Car/car	Dry, clear, daylight
Lane changes/side swipe	**305**	3	Car/truck – 3	Dry, clear, daylight – 3
Off Carriageway on straight hit object	**703**	1	Bicycle/car	Dry, clear, daylight
Opposing vehicle turning	**202**	2	Car/car/car – 1 Car/car – 1	Dry, clear, daylight – 2
	203	2	Car/car – 2	Dry, clear, daylight – 1 Dry, clear, Darkness (lighted) – 1
Rear-end	**301**	1	Car/car/car	Dry, clear, daylight
Vehicle leaving driveway	**406**	1	Car/car	Dry, clear, daylight
Other	**400**	1	Bicycle/car	Dry, clear, daylight

Two out of three of the single vehicle crashes occurred during wet/raining conditions and the other at dawn/dusk lighting conditions which would be significant contributing factors to these crashes.

This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess hit object crashes compared to the other top 10 roundabouts.

It was also identified during this investigation that the three sideswipe crashes that have occurred at this roundabout have all involved trucks which needs to be further investigated to ensure the roundabout is an adequate design for the travel of trucks (unfortunately the crash data available did not include details about the kind of trucks involved). It was identified through the use of Queensland Globe on Google Earth that each of the three sideswipe crashes that occurred all occurred on the north entry and carriageway, Figure 4.12. To investigate these crashes properly the full crash reports should be examined to determine details such as: the type of truck involved; if it was in the entry, carriageway or exit; which lane the two vehicles were in and which vehicle crossed into the wrong lane. If trends are identified, then there would be a strong indication that the geometry requires review.

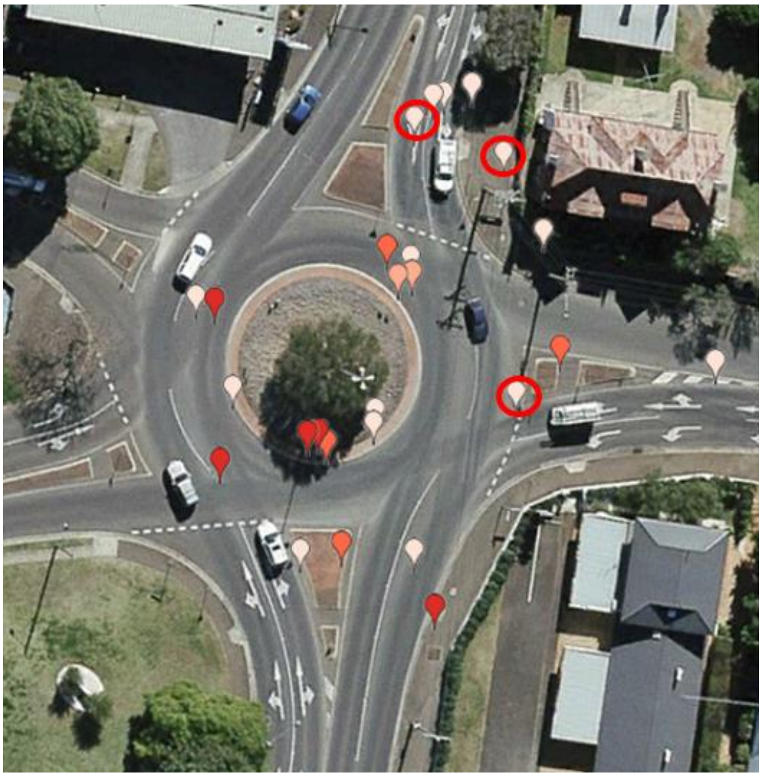


Figure 4.12: Truck sideswipe crashes at NW6 roundabout (circled in red) (Google Earth 2016)

The north and south approaches (West Street) are both two lane roads and continue through the roundabout as two lanes and as expected have the highest traffic volume at 37% and 32% respectively. The east approach and south-west approach have similar traffic volumes to each other at 15% and 12% respectively and the north-west approach has significantly less traffic at only 4% of the total traffic volume at the roundabout.

NW6 Road Safety Audit

The key findings from the road safety audits include:

- Vehicles appeared to enter the roundabout at relatively high speed;
- No provision for cyclists;
- Traffic crossing centreline separating the lanes;
- No trafficable apron;
- Central trees obscures vision of other side of roundabout, Figure F.10;
- 8 power/light poles and 6 trees within the clearance zone Figure F.11;
- Unique roundabout layout and lack of signage prior to entry can cause confusion for motorists Figure F.12;
- Faded line marking Figure F.14;
- Service station entry off the roundabout carriageway effectively adds a 6^{th} exit off the round abound Figure F.15;
- Sight distance on south approach below average; concrete wall and hedge obstruct view;
- Sight distance on east approach impeded by a high fence and vegetation Figure F.18;
- Sight distance from the south west approach is impeded by vegetation; and
- Car parking on the eastern approach has potential to limit pedestrian sight distance Figure F.21.

The geometric properties of this roundabout are summarised in Table 4.11.

Table 4.11: Geometric properties for NW6 roundabout

		Roundabout Leg				
		North	**South**	**East**	**North-west**	**South-west**
Centre Island Diameter (m)		20				
Inscribed Circle Diameter (m)		31 (inner lane) and 41 (outer lane)				
Circulating Roadway Width (m)		5.4	5.8	10.5	10.5	10.7
		Vehicle paths would need to be checked before changes were made				
Weaving Width (m)		10.3	14.4	11.5	10.9	13.5
Weaving Length (m)		18.4	13.2	19.7	13.7	13.2
Approach Width (m)		6.7	7	4	4.5	4.5
Entry Width (m)		7.5	11	6	4.3	7.3
Exit Width (m)		7	9.8	6.7	5.3	5.2
Eccentricity (m)		-4.8	5.7	4	0	4.4
Angle to Next Leg (degrees)		82.1	88.7	61.5	55.4	72.3
Deflection Radius (m)		130	50	200	140	-
Approach Gradient (%)		0.3	2.5	2.9	-2.0	-2.9
Entry Path Radius (m)	**Left lane**	25	45			
	Right lane	30	65	75	70	25
	Crossing lanes	75	90			

4.4.4 Rank 3: SW6 – Glenvale Road and Greenwattle Street

SW6 – Glenvale Road and Greenwattle Street roundabout was ranked as the third worst performing roundabout in Toowoomba. Figure 4.13 shows the crashes that have occurred at the roundabout throughout the study period represented by the coloured pins.

Figure 4.13: SW6 - Glenvale Road and Greenwattle Street roundabouts crash diagram (Google Earth 2016)

SW6 Crash Investigation

There was a total of 16 crashes recorded at SW6 during the study period which were all multiple vehicle, angle crashes. This roundabout has the second lowest traffic volume out of the identified top 10 roundabouts and yet had the second highest number of crashes which resulted in a high calculated crash rate. The traffic volume on the south and west approaches is significantly higher at 31% and 30% respectively than the north approach at 24% and the west approach with only 15%.

The 16 crashes that were recorded at this roundabout were all multiple vehicle, angle crashes that fell into the DCA group ‘Intersection from adjacent approaches’ with DCA code 101 except for one crash which was DCA code 107. This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess angle crashes compared to the other top 10 roundabouts.

The following combination of environmental conditions were observed:

- Dry, clear, daylight – 10 crashes;

- Wet, raining, daylight – 2 crashes;
- Wet, foggy, darkness (lighted) – 1 crash;
- Wet, foggy, dawn/dusk – 1 crash; and
- Dry, clear, Darkness (lighted) – 1 crash.

There were a number of road users involved in crashes at this roundabout, as shown below:

- 2 cars – 11 crashes;
- Bicycle and car – 2 crashes;
- Motorcycle and car – 1 crash; and
- Truck and car – 2 crashes.

The crash severity for the crashes included; 10 property damage only, 1 minor injury, 1 medical treatment and 4 hospitalisations. The 2 crashes that involved a bicycle road user and the 1 crash that involved a motorcycle road user all resulted in a hospitalisation.

SW6 Road Safety Audit

The key findings from the road safety audits include:

- High speeds observed;
- Shared zone bicycle symbols on east and west legs;
- Sight distance excessive on south and west approaches due to undeveloped;
- Vacant land on south-east and south-west corners;
- Sight distance on east approach largely obscured by a fence;
- Trafficable apron around central island Figure F.22;
- Significant cross fall from east to west across roundabout Figure F.23;
- Pedestrian crossing storage absent in splitter island of north leg Figure F.24;
- Trafficable apron flush with bitumen seal on eastern side Figure F.25; and

- 4 light/power poles and 1 tree identified in clearance zone of roundabout, Figure F.26.

The geometric properties of this roundabout are summarised in Table 4.12.

Table 4.12: Geometric properties of SW6 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	12			
Inscribed Circle Diameter (m)	27			
Circulating Roadway Width (m)	7.5	7.2	7	7.5
Weaving Width (m)	7.6	7.2	7.8	8.2
Weaving Length (m)	14.4	15.6	15.4	14.9
Approach Width (m)	4.5	4.3	3.1	3.1
Entry Width (m)	3.7	3.5	4.3	4.2
Exit Width (m)	4.6	4.2	4.3	4.1
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	50	55	65	180
Approach Gradient (%)	-1.3	1.3	-5.9	5.7
Entry Path Radius (m)	55	50	85	95

4.4.5 Rank 4: NW7 – North Street and Tor Street

NW7 – North and Tor Street roundabout was ranked as number 4 in Toowoomba based on the safety performance of the roundabout. Figure 4.14 shows the crashes that have occurred at the roundabout throughout the study period represented by the coloured pins.

Figure 4.14: NW7 - North Street and Tor Street roundabout crash diagram (Google Earth 2016)

NW7 Crash Investigation

There was a total of 9 crashes recorded at NW7 during the study period which included 8 multiple vehicle, angle crashes as well as 1 single vehicle, hit pedestrian crash. The traffic volume between the legs are very similar; north approach (27%), south approach (23%), east approach (27%) and west approach (23%).

There were 7 crashes that fell into the DCA group 'Intersection from adjacent approaches' which all had the DCA code 101. The remaining two crashes fell into DCA groups 'Pedestrian' and 'Opposing vehicles turning' with DCA codes 2 and 202 respectively. This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess angle crashes compared to the other top 10 roundabouts.

The following combination of environmental conditions were observed in the crash data:

- Dry, clear, daylight – 5 crashes;
- Wet, raining, daylight – 1 crash;
- Wet, clear, daylight – 1 crash; and
- Dry, clear, dawn/dusk – 2 crashes.

There were also a number of road users involved in crashes at this roundabout. The road users involved in crashes included:

- 2 cars – 4 crashes;
- Motorcycle and car – 2 crashes;
- Other vehicle and car – 1 crash; and
- Pedestrian and car – 1 crash.

The crash severity for the crashes included; 2 property damage only, 1 medical treatment and 6 hospitalisations. There is a significant number of hospitalisation crashes, 4 of which include the two motorcycle crashes, the pedestrian crash and the other vehicle crash. This suggests that speed is an issue at this roundabout due to the higher severity of crashes.

NW7 Road Safety Audit

The key findings from the road safety audits include:

- High speeds observed;
- No provision for cyclists;
- On street parking all legs may affect stopping sight distance on south approach;
- Trafficable apron on Central Island, Figure F.27;
- 8 light/power poles identified in clearance zone, Figure F.28;
- Fence/hedges found on corners except the south-west corner in clearance zone;
- Sight distance for the north, east, and west approaches below average;
- High pressure gas main within clearance zone, Figure F.30;
- Splitter islands displaying severe cracking, Figure F.31;

- Power/light poles installed in centre of footpath on southern leg, Figure F.32; and
- Parked cars potentially affect sight distance.

The geometric properties of this roundabout are summarised in Table 4.13.

Table 4.13: Geometric properties of NW7 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	10			
Inscribed Circle Diameter (m)	25			
Circulating Roadway Width (m)	7.3	7.3	7.9	6.8
Weaving Width (m)	7	7.4	7.5	6.8
Weaving Length (m)	14.5	13.6	14.5	13.5
Approach Width (m)	4.5	4.8	4.7	4.6
Entry Width (m)	3.5	3.5	3.3	3.5
Exit Width (m)	3.7	3.3	3.4	3.3
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	60	70	55	60
Approach Gradient (%)	-1.4	1.9	3.6	-4.2
Entry Path Radius (m)	45	60	55	45

4.4.6 Rank 5: SE21 – Spring Street and Hume Street

SE21 – Spring and Hume Street roundabout was ranked number 5 of the worst performing roundabouts in Toowoomba. Figure 4.15 shows that crashes (coloured pins) that were recorded at this roundabout during the study period.

Figure 4.15: SE21 - Spring Street and Hume Street roundabout crash diagram (Google Earth 2016)

This roundabout only recently (2015/2016) had an additional left turn lane installed on the northern leg due to the high volume of traffic that turn left at this roundabout, see the more updated imagery in Figure 4.16.

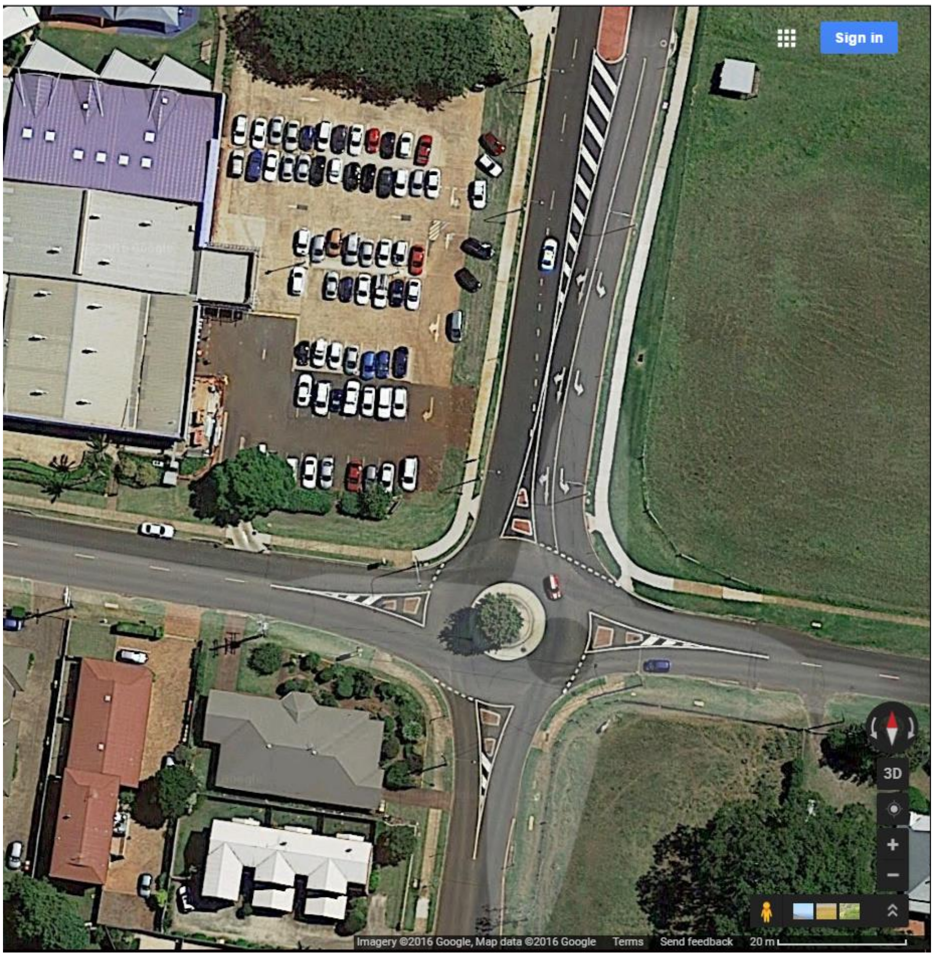


Figure 4.16: SE21 - Spring Street and Hume Street roundabout new left turn lane (Google Maps 2016)

SE21 Crash Investigation

There was a total of 10 crashes recorded at SE21 during the study period which included 9 multiple vehicle, angle crashes and 1 single vehicle, fall from vehicle crash which involved a motorcycle. The traffic volume between the legs are relatively similar on the north and west approaches of 28% and 29% respectively. The east approach has 26% and south approach has the least traffic with only 17% of the traffic volume.

There were four DCA groups that the crashes at this roundabout fell into. These were:

- Intersection from adjacent approaches – 7 crashes all with DCA code 101;
- Opposing vehicles turning – 1 crash with DCA code 202 which involved a car and bicycle;
- Vehicle leaving driveway – 1 crash with DCA code 408 which involved a bicycle entering from a footway; and

- Off carriageway on straight – 1 crash with DCA code 706 which involved a motorcyclist.

This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess angle crashes compared to the other top 10 roundabouts.

The following combination of environmental conditions were observed in the crash data:

- Dry, clear, daylight – 5 crashes;
- Dry, clear, darkness (lighted) – 2 crashes;
- Dry, clear, dawn/dusk – 1 crash;
- Wet, raining, darkness (lighted) – 1 crash; and
- Wet, raining, dawn/dusk – 1 crash.

There were also a number of road users involved in crashes at this roundabout. The road users involved in crashes included:

- 2 cars – 7 crashes;
- Bicycle and car – 2 crashes; and
- Motorcycle – 1 crash.

The crash severity for the crashes included; 5 property damage only, 1 minor injury, 3 medical treatment and 1 hospitalisation. The hospitalisation crash involved a bicycle rider and two out of the three medical treatment crashes involved the other bicycle and a motorcycle.

SE21 Road Safety Audit

The key findings from the road safety audits include:

- High speeds observed;
- High traffic volumes largely due to proximity to shops and two schools;
- School signs partially obscured by power/light posts on each leg, Figure F.37 and Figure F.38;

- Sight distance varies, excessive from the east approach while south approach was above average due to undeveloped. The west approach has below average sight distance due to vegetation;
- Trafficable apron around central island; and
- Tree in central island, Figure F.35.

The geometric properties of this roundabout are summarised in Table 4.14.

Table 4.14: Geometric properties of SE21 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	12			
Inscribed Circle Diameter (m)	26			
Circulating Roadway Width (m)	6.7	7	6.8	6.5
Weaving Width (m)	11.4	8.8	8.1	6.8
Weaving Length (m)	13.4	14.1	13.9	13.8
Approach Width (m)	7	5	4.4	4.8
Entry Width (m)	8	3.8	3.3	3.6
Exit Width (m)	4.3	4.7	5.2	5.5
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	60	70	180	80
Approach Gradient (%)	3.2	-5.0	-0.5	1.2
Entry Path Radius (m)	55	90	80	50

4.4.7 Rank 6: SE14 – Alderley Street and Ramsay Street

SE14 was ranked number 6 of the top 10 worst performing roundabouts in Toowoomba. Figure 4.17 shows the crashes that have been recorded at this roundabout during the study period, shown by the coloured pins.

Figure 4.17: SE14 - Alderley Street and Ramsay Street roundabout crash diagram (Google Earth 2016)

SE14 Crash Investigation

There was a total of 11 crashes recorded at SE14 during the study period which included 8 multiple vehicle, angle crashes, 1 multiple vehicle hit object crash which resulted in two fatalities and 2 single vehicle, hit object crashes. The traffic volume between the legs are as follows: north approach (25%), south approach (29%), east approach (20%) and west approach (26%).

The 8 multiple vehicle, angle crashes and the one multiple vehicle, hit object crash all fell into the DCA group of 'Intersection from adjacent approaches' with the DCA code 101. The two single vehicle, hit object crashes fall into the DCA group 'Off carriageway on straight hit object' with DCA code 703 and 704. This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess hit object crashes compared to the other top 10 roundabouts.

The following combination of environmental conditions were observed in the crash data:

- Dry, clear, daylight – 4 crashes;
- Dry, clear, darkness (lighted) – 2 crashes;
- Dry, foggy, dawn/dusk – 1 crash;
- Wet, raining, daylight – 1 crash;
- Wet, raining, darkness (lighted) – 2 crashes; and
- Wet, foggy, daylight – 1 crash.

Weather conditions such as wet road, rain and fog were a factor in 5 out of 11 of the crashes at this roundabout.

The only road user involved in crashes at this roundabout during the study period were cars. The crash severity for the crashes included; 7 property damage only crashes, 2 medical treatment crashes, 1 hospitalisation crash and 1 fatal crash.

The fatal crash at this roundabout occurred during wet, foggy, daylight conditions and involved two cars. An image from a newspaper article showing the foggy conditions can be seen in Figure 4.18.

Figure 4.18: Fatal crash that occurred at SE14 roundabout during foggy conditions (Donaghey 2006)

<u>SE14 Road Safety Audit</u>

The key findings from the road safety audits include:

- Trafficable apron around central island;
- Tree on central island, Figure F.39;

- 8 power/ light poles and 3 trees in the clearance zone, Figure F.40 and Figure F.41;
- Faded line marking, Figure F.42;
- Driveway to residence and its proximity to north roundabout entry carriageway potential conflict point, Figure F.43; and
- Slight crest on south leg on approach, Figure F.44 and Figure F.45.

The geometric properties of this roundabout are summarised in Table 4.15.

Table 4.15: Geometric properties of SE14 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	10			
Inscribed Circle Diameter (m)	24			
Circulating Roadway Width (m)	6.7	6.7	7	7
Weaving Width (m)	7	7.1	7.2	7.3
Weaving Length (m)	12.6	13.6	12.8	13.4
Approach Width (m)	5	5	4.7	5.1
Entry Width (m)	3.5	3	3.2	3.2
Exit Width (m)	3.1	3.1	3.4	3
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	65	45	60	60
Approach Gradient (%)	2.8	3.0	3.2	-5.1
Entry Path Radius (m)	70	80	60	70

4.4.8 Rank 7: SE12 – South Street and MacKenzie Street

SE12 was ranked number 7 of the top 10 worst performing roundabouts in Toowoomba. Figure 4.19 shows the crashes that have been recorded at this roundabout during the study period, shown by the coloured pins.

Figure 4.19: SE12 - South Street and MacKenzie Street roundabout crash diagram (Google Earth 2016)

SE12 Crash Investigation

There was a total of 9 crashes recorded at SE12 during the study period which were all multiple vehicle, angle crashes. The traffic volume differs greatly between each leg: north approach (39%), south approach (33%), east approach (18%) and west approach (10%).

All 9 of the crashes fell into the DCA group Intersection from adjacent approaches, 8 of the crashes were DCA code 101 and one was DCA code of 102. This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess angle crashes compared to the other top 10 roundabouts.

Eight of the crashes occurred during dry, clear, daylight conditions and the other crash occurred during dry, clear conditions at dawn/dusk. All 9 of the crashes involved 2 cars.

The crash severity for the crashes included 6 property damage only crashes, 1 medical treatment crash and 2 hospitalisation crashes.

The sight distance on the south and west approaches were considered excessive because of the vacant parkland on the south-east and south-west corners of the roundabout. Similarly, the sight distance for the north approach was considered above average due to the parkland on the north-west corner of the roundabout. Unfortunately, the sight distance for the east approach is significantly reduced due to a large tree and high fence so was considered to be poor.

SE12 Road Safety Audit

The key findings from the road safety audits include:

- Very high entry speeds;
- Nearby flood warning signs suggest the intersection floods during heavy rainfall
- Central Island has no trafficable apron, has light pole in the middle with reflective arrows around its perimeter, Figure F.46;
- 6 power/light poles and one large tree in the clearance zone, Figure F.47;
- Broken lines advise of cyclists on south and north legs, Figure F.48 and Figure F.49, and bicycle symbol is extremely faded, Figure F.50;
- Sight distance reduced due to large tree on north-east corner, Figure F.51; and
- Line marking faded and cracked in places, Figure F.52.

The geometric properties of this roundabout are summarised in Table 4.16.

Table 4.16: Geometric properties of SE12 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	14			
Inscribed Circle Diameter (m)	32			
Circulating Roadway Width (m)	8.7	8.6	8.7	9
	Adequate for single unit truck			
Weaving Width (m)	8.9	8.2	9.5	8.7
Weaving Length (m)	19.5	19.7	16.1	16.1
Approach Width (m)	4.5	4.4	4.5	4.7
Entry Width (m)	4.6	3.8	3.7	3.8
Exit Width (m)	4.8	4.3	4.8	4.7
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	102	82	98	78
Deflection Radius (m)	75	70	65	60
Approach Gradient (%)	-0.6	2.6	-3.9	0.0
Entry Path Radius (m)	120	80	65	65

4.4.9 Rank 8: SE13 – Alderley Street and Hume Street

SE13 was ranked number 8 of the top 10 worst performing roundabouts in Toowoomba. Figure 4.20 shows the crashes that have been recorded at this roundabout during the study period, shown by the coloured pins.

Figure 4.20: SE13 - Alderley Street and Hume Street roundabout crash diagram (Google Earth 2016)

SE13 Crash Investigation

There was a total of 15 crashes recorded at SE13 during the study period which are summarised in Table 4.17. The traffic volumes distribution between the legs at this roundabout were: north (25%), south (26%), east (23%) and west (26%).

Table 4.17: Crash summary for SE13 roundabout

SINGLE VEHICLE CRASHES				
DCA Group	**DCA code**	**Total**	**Road User**	**Conditions**
Off carriageway on straight	**707**	1	Motorcycle	Dry, clear, daylight
Off carriageway on straight hit object	**703**	1	Car	Wet, raining, daylight
Hit parked vehicle	**601**	1	2 cars	Dry, clear, daylight
MULTIPLE VEHICLE CRASHES				
DCA Group	**DCA code**	**Total**	**Road Users**	**Conditions**
Intersection from adjacent approaches	**101**	**7**	Car/car – 5 Car/motorcycle – 1 Car/truck – 1	Dry, clear, daylight – 4 Wet, raining, darkness (lighted) – 2 Wet, raining, dawn/dusk - 1
Rear-end	**301**	3	Car/car – 2 Car/car/car – 1	Dry, clear, daylight – 1 Dry, clear, darkness (lighted) – 1 Wet, raining, daylight – 1
	303	1	Car/car	Dry, clear, daylight
HIT PEDESTRIAN				
DCA Group	**DCA code**	**Total**	**Road Users**	**Conditions**
Pedestrian	**1**	1	Car/pedestrian	Dry, clear, daylight

This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess rear-end crashes compared to the other top 10 roundabouts.

The crash severity for the crashes included; 5 property damage only crashes, 1 minor injury crash, 8 medical treatment crashes and 1 hospitalisation crash.

<u>SE13 Road Safety Audit</u>

The key findings from the road safety audits include:

- High traffic volume, traffic banks up outside of peak hour;

- 8 power/light poles and 7 trees inside the clearance zone, Figure F.53;
- Trafficable apron and single tree in the centre, Figure F.54;
- Highest traffic volume of all top ten roundabouts, Figure F.55;
- Yellow shared bicycle symbols on all of the round legs, Figure F.56;
- Sight distance from west approach considered poor due to fencing and vegetation, Figure F.57; and
- Sight distance from south approach was below average due to vegetation on the south east corner, Figure F.58.

The geometric properties of this roundabout are summarised in Table 4.18.

Table 4.18: Geometric properties of SE13 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	10.5			
Inscribed Circle Diameter (m)	25.5			
Circulating Roadway Width (m)	7.1	7.2	7.2	7.3
Weaving Width (m)	6.7	6.7	6.4	7.3
Weaving Length (m)	15.1	14.8	13.8	13.7
Approach Width (m)	6.5	4.7	4.4	4.9
Entry Width (m)	4.7	3	3.1	3.4
Exit Width (m)	4.3	2.8	3	3
Eccentricity (m)	0	0	0	0
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	60	70	55	50
Approach Gradient (%)	-1.5	1.6	-3.3	3.4
Entry Path Radius (m)	75	45	35	50

4.4.10 Rank 9: SE15 – Alderley Street and MacKenzie Street

SE15 was ranked number 9 of the top 10 worst performing roundabouts in Toowoomba. Figure 4.21 shows the crashes that have been recorded at this roundabout during the study period, shown by the coloured pins.

Figure 4.21: SE15 - Alderley Street and MacKenzie Street roundabout crash diagram (Google Earth 2016)

SE15 Crash Investigation

There was a total of 9 crashes recorded at SE15 during the study period which were all multiple vehicle crashes including 7 angle crashes and 2 rear-end crashes. The traffic volume distribution between the legs are: north (30%), south (27%), east (25%) and west (19%).

The crashes fall under two DCA group codes: Intersection from adjacent approaches – where 5 of the crashes were DCA code 101 and two were DCA code 104; and Rear-end where there was 1 DCA code 301 crash and 1 DCA code 303 crash. This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess rear-end crashes compared to the other top 10 roundabouts.

There were 4 crashes out of the total 9 crashes that involved a bicycle and a car at this roundabout. The remaining 5 crashes all involved two cars.

The environmental conditions observed for all of the crashes included: dry and clear conditions with 7 of the crashes occurring at daylight, 1 crash at dawn/dusk and 1 crash in darkness (lighted).

SE15 Road Safety Audit

The key findings from the road safety audits include:

- High speed of entering traffic;
- Sight distance from east and west approaches considered to be below average due to vegetation on north east and south west corners, Figure F.64;
- Sight distance from the south is poor due to a crest that rises immediately before entry to the roundabout, Figure F.63;
- Central island has no trafficable apron, Figure F.59;
- Vegetation in central island obscures view of other side of roundabout on east and west approaches, ;
- No provision for cyclists;
- 8 power/light poles and one tree identified in the clearance zone, Figure F.61; and
- East approach is on a significant uphill grade, inhibiting sight distance both across roundabout and to traffic entering from the north approach, Figure F.62.

The geometric properties of this roundabout are summarised in Table 4.19.

Table 4.19: Geometric properties of SE15 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	10			
Inscribed Circle Diameter (m)	26			
Circulating Roadway Width (m)	7.5	7.5	7.5	7.8
	Adequate for single unit truck			
Weaving Width (m)	7.2	7.4	7.1	7.2
Weaving Length (m)	15	13.8	13.6	14.5
Approach Width (m)	4.8	4.8	4.2	4.8
Entry Width (m)	3.5	3	3.3	3.1
Exit Width (m)	3.5	3.3	3.9	3.2
Eccentricity (m)	0	0	0	1.3
Angle to Next Leg (degrees)	90	90	90	90
Deflection Radius (m)	50	75	130	45
Approach Gradient (%)	-0.4	0.6	6.9	-3.8
Entry Path Radius (m)	50	55	60	45

4.4.11 Rank 10: SW1 – Alderley Street and Drayton Road

SW1 was ranked number 10 of the top 10 worst performing roundabouts in Toowoomba. Figure 4.22 shows the crashes that have been recorded at this roundabout during the study period, shown by the coloured pins.

Figure 4.22: SW1 - Alderley Street and Drayton Road roundabout crash diagram (Google Earth 2016)

SW1 Crash Investigation

There was a total of 11 crashes recorded at SW1 during the study period which included 1 single vehicle, hit object crashes; 9 multiple vehicle crashes – which included 4 angle crashes, 3 rear-end crashes, 1 head on crash and 1 other crash; and 1 hit pedestrian crash. The head on crash occurred on the east approach (see red circle on Figure 4.22, although this location is only approximate). This is very unusual at a roundabout particularly where there is a median separating the east and west bound traffic. The exact circumstances of this crash are not known due to the limited information provided in the crash data which simply states that it was a head on crash between 2 cars at approximately 2pm during dry, clear conditions.

The traffic volume distribution between the legs are: north (19%), south (24%), east (26%) and west (31%). The traffic on the west approach is significantly higher and the traffic on the north approach considerably lower.

The single vehicle crash fell into the DCA group Off carriageway on straight hit object with DCA crash code 703 and the hit pedestrian crash fell into the DCA group of Pedestrian with the DCA code of 3.

The multiple vehicle crashes fell into 6 different DCA groups. These were:

- Intersection from adjacent approaches – 2 crashes with DCA code 101;
- Opposing vehicles turning – 1 crash with DCA code 202;
- Rear-end – 2 crashes with DCA codes 302 and 1 crash with DCA code 303;
- Vehicle leaving driveway – 1 crash with DCA code 408;
- Other – 1 crash with DCA code 900; and
- Head-on – 1 crash with DCA code 201.

This roundabout was identified by the excess proportion of specific crash type method as having a high probability of excess rear-end crashes compared to the other top 10 roundabouts.

There was 1 single vehicle crash, 6 crashes involving 2 cars, 1 crash involving a car and bicycle, 2 crashes involving a car and motorcycle and 1 crash involving a car and pedestrian.

The environmental conditions observed for all of the crashes included; dry, clear and daylight conditions for 7 of the crashes; dry, clear, darkness (lighted) for 3 of the crashes and wet, raining and daylight for 1 of the crashes.

The crash severity for the crashes included:

- 3 property damage only crashes;
- 2 minor injury crashes;
- 5 medical treatment crashes; and
- 1 hospitalisation crash.

SW1 Road Safety Audit

The key findings from the road safety audits include:

- High entry speeds observed during site visit;

- Roundabout legs not perpendicular to each other;
- Sight distance below average on south approach to vegetation on south east corner, Figure F.68;
- Poor sight distance on east approach due to dense vegetation on the north east corner including a large tree, Figure F.69;
- Central island has no trafficable apron and has rock and a light pole at its centre;
- 6 power/light poles identified within the clearance zone, Figure F.67;
- Sight distance on south approach below average due to vegetation on south-east corner, Figure F.68;
- Sight distance on east approach poor due to dense vegetation obscuring view of north east corner, Figure F.69;
- Yellow shared zone for cyclists on all four legs as well as signs advising other road users to be watchful for cyclists, Figure F.71; and
- Some line marking beginning to fade, Figure F.72.

The geometric properties of this roundabout are summarised in Table 4.20.

Table 4.20: Geometric properties of SW1 roundabout

	Roundabout Leg			
	North	**South**	**East**	**West**
Centre Island Diameter (m)	15			
Inscribed Circle Diameter (m)	30			
Circulating Roadway Width (m)	7.3	6.6	6.5	7
	Adequate for single unit truck			
Weaving Width (m)	11.4	10.5	6.6	7.4
Weaving Length (m)	12.8	12.6	19.5	22.7
Approach Width (m)	5	5	4.8	4
Entry Width (m)	5.7	4.4	5	4.6
Exit Width (m)	4.7	4.7	6.5	5
Eccentricity (m)	3.5	2.6	3.7	3.7
Angle to Next Leg (degrees)	69	87	83	121
Deflection Radius (m)	120	40	85	45
Approach Gradient (%)	3.7	0.9	3.1	-2.8
Entry Path Radius (m)	40	60	45	45

4.5 Proposed Remedial Measures

As has been discussed in the literature the most significant contributing factor to improving the crash rate at roundabouts is reducing the speed of entering vehicles, (Austroads 2015b). The two most important geometric properties of roundabouts that influence the speed of vehicles are adequate sight distance and entry geometry, (Austroads 2015b).

The crash improvements by reducing the speed at roundabouts are significant. There are several treatments that can improve the crash rate at a roundabout including: reduce the deflection radius – which minimises the speed of vehicles within the carriageway, , entry path radius – which aims to limit the vehicle speed prior to the entry to the roundabout (Austroads 2015b).

The entry path radius should be designed in combination with the centre island diameter and together improves the vehicle speed as the road user is required to navigate a tighter curve, thus reducing the number of accidents. (Arndt 2008)

4.5.1 Rank 1: SW7 – Glenvale Road and McDougall Street

High entry speeds were observed during the site visit at SW7 which is one of the most likely causes of the high number of angle crashes observed at this roundabout.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – currently all of the legs have an entry path radius greater than the maximum in particular the east and west approaches which have entry path radii of 75 and 85m respectively;
- Reduce entry width – up to the minimum of 3.0m; and
- Install reverse curves to progressively slow vehicles upon approach to the roundabout.

  (Austroads 2015b)

The vegetation on the south-east and south-west corners of the roundabout should be regularly maintained to ensure the sight distance is not obstructed for vehicles approaching on the south leg.

Re-apply the bicycle symbols to the east and west legs to increase visibility of the symbol to improve driver awareness of bicycles at the roundabout.

Finally, investigate the possibility of relocating some of the power/light poles so that they are in a less critical part of the clearance zone.

4.5.2 Rank 2: NW6 – Anzac Avenue, Russell Street and West Street

High entry speeds were observed during the site visit at NW6 which is one of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that the south approach, east approach and north-west approach have insufficient entry path radii of 65, 75 and 70m respectively;
- Reduce entry width – up to the minimum of 3.0m per lane; and
- Install reverse curves to progressively slow vehicles upon approach to the roundabout – it was noted there is currently a reverse curve in place on the north approach which results in an entry path radius of 30m from the right lane and 25m from the left lane which is significantly lower than the maximum of 55m. However, if the entry path radius is considered for crossing lanes.

  (Austroads 2015b)

Some other remedial treatments identified include:

- The removal or relocation of some of the 8 power/light poles and 6 trees should be investigated due to the excess of hit object crashes that was identified at this roundabout using the excess proportion of specific crash type method;
- The dense vegetation of the two trees in the centre island could be thinned out to allow more vision around the roundabout;
- Installation of directional signage to advise road users in advance which lane to be in to improve the confusion road users experience due to the unique layout of this roundabout;

- Re-apply the line marking throughout the roundabout to improve the clarity of the travel path of the road user through the roundabout;

- Install RRPM's (Raised Retro-reflective Pavement Markers) across the centre line of the two circulating lanes to encourage drivers not to cross the centre line – cars were witnessed crossing this centre line during the road safety audit site investigations;

- Investigate the possibility of either restricting the service station entry from the roundabout to 'trucks only' or if possible, removing/relocating it;

- Remove/reduce the vegetation on the south-west corner to improve the sight distance for pedestrians crossing the southern leg and traffic on the south-west approach; and

- Investigate possible improvements of sight distance for south approach and east approach by reducing vegetation on the north-east and south-east corners.

4.5.3 Rank 3: SW6 – Glenvale Road and Greenwattle Street

High entry speeds were observed during the site visit at SW6 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that the east and west approaches have insufficient entry path radii of 85 and 95 respectively;

- Reduce entry width – up to the minimum of 3.0m;

- Install reverse curves to progressively slow vehicles upon approach to the roundabout; and

- Reduce deflection radius on the west approach to less than 100m – it was measured to be 180m.

  (Austroads 2015b)

Some other remedial treatments identified include:

- Install a longer splitter island on the north leg that includes a pedestrian storage area to improve pedestrian safety;
- Assess the height of the trafficable apron in some areas of the carriageway and if found to be too low investigate increasing the height to ensure road users such as cars are not encouraged to traverse the apron; and
- Improve the approach gradients on the east (-5.9%) and west (5.7%) legs where feasible – at a minimum, investigate feasibility of at least providing a flat area (max 2-3%) on immediate approach to accommodate length of one design vehicle.

  (Austroads 2015b)

4.5.4 Rank 4: NW7 – North Street and Tor Street

High entry speeds were observed during the site visit at NW7 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce entry width – up to the minimum of 3.0m;
- Increase the centre island diameter and associated geometry – the central island is currently the minimum recommended size of 10m, increasing the size of the central island would be expected to improve crash rates; and
- Install reverse curves to progressively slow vehicles upon approach to the roundabout.

  (Austroads 2015b)

Another remedial treatment identified included:

- Improve sight distance for north, east and west approaches by reducing vegetation on the north-west, north-east and south-east corners.

4.5.5 Rank 5: SE21 – Spring Street and Hume Street

Some remedial treatments identified for the geometric properties include:

- Improve the deflection radius on the east leg which is 180m when the maximum through the roundabout is 100m;
- Reduce the entry path radius on the south and east approaches as they exceed the maximum radius of 55m with values of 90 and 80m respectively;
- Improve the approach gradient on the south leg which is at a grade of -5.0% (downhill); and
- Reduce entry width – up to the minimum of 3.0m.

Some other remedial treatments identified include:

- Relocate the school zone signs on the north leg that are installed behind the light poles on both sides of the road to improve their view; and
- Improve sight distance on the west approach by removing/reducing some vegetation.

4.5.6 Rank 6: SE14 – Alderley Street and Ramsay Street

High entry speeds were observed during the site visit at SE14 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that all of the approaches have insufficient entry path radii of north (70m), south (80m), east (60) and west (70) respectively;
- Reduce entry width – up to the minimum of 3.0m;
- Install reverse curves to progressively slow vehicles upon approach to the roundabout; and
- Increase the size of the central island as it is the minimum recommended size.

(Austroads 2015b)

Some other remedial treatments identified include:

- Re-apply line markings to ensure it is clear to road users how to traverse the roundabout; and
- Investigate removing/relocating the poles and trees to a less critical zone of the clearance zone (8 poles and 3 trees)

4.5.7 Rank 7: SE12 – South Street and MacKenzie Street

High entry speeds were observed during the site visit at SE12 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that all of the approaches have insufficient entry path radii of north (120m), south (80m), east (65) and west (65) respectively;
- Reduce entry width – up to the minimum of 3.0m;
- Install reverse curves to progressively slow vehicles upon approach to the roundabout; and
- Increase the size of the central island as it is the minimum recommended size.

  (Austroads 2015b)

Some other remedial treatments identified include:

- Re-apply the faded line marking to ensure road users are not confused;
- Improve the sight distance on the east approach by removing/reducing some of the vegetation obstructing the visibility;
- Investigate the removing or relocating some of the poles to less critical areas within the clearance zone; and
- Bicycle lanes on north and south approaches should be signed and/or the yellow bicycle “shared zone” symbols should be re-painted. The lanes were not easily identifiable as bicycle lanes.

4.5.8 Rank 8: SE13 – Alderley Street and Hume Street

Some possible remedial treatments include:

- Reduce the entry path radius on the north approach to be below the maximum 55m – it was measured to be 75m;
- Reduce entry width – up to the minimum of 3.0m;
- Increase the centre island diameter as it is currently only just larger than the minimum required – increasing the centre island diameter would provide more separation between legs which allows for more reaction time for a car entering immediately from the right, particularly in heavy traffic as is experienced here (3^{rd} highest traffic volume out of top 10 roundabouts) when cars are often approaching slowly and/or stopped before entering;
- Improve sight distance for west and south approaches by reducing/removing vegetation on south-west and south-east corners where possible; and
- Investigate relocating/removing some of the power poles and/or trees within the clearance zone of this roundabout. There are 8 poles and 7 trees which is a considerable number and there have been two 'off carriageway hit object crashes' during the study period.

4.5.9 Rank 9: SE15 – Alderley Street and MacKenzie Street

High entry speeds were observed during the site visit at SE15 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that the east approach has an insufficient entry path radius of 60m (this could just be measurement inaccuracy due to using aerial imagery);
- Reduce deflection radius through the roundabout for south and east approaches – they were measured at 75 and 130m respectively;
- Reduce entry width – up to the minimum of 3.0m;

- Install reverse curves to progressively slow vehicles upon approach to the roundabout; and
- Increase the size of the central island as it is the minimum recommended size.

  (Austroads 2015b)

Some other possible remedial treatments identified include:

- Install prior warning signage for the east approach advising that there is a roundabout ahead – the approach is on a significant uphill grade of 6.9%;
- Install prior warning signage for the south approach advising that there is a roundabout ahead – there is a crest upon approach to the roundabout;
- Improve the approach gradient on the east approach (measured to be 6.9%) – at a minimum, investigate feasibility of at least providing a flat area (max 2-3%) on immediate approach to accommodate length of one design vehicle (Austroads 2015b);
- Install yellow ‘shared zone’ bicycle symbols and/or associated signage to increase road user awareness of bicycles at the intersection – 4/9 of the crashes during the study period involved a bicycle and a car;
- Improve sight distance on south, east and west approaches by reducing/removing vegetation on the north-east, south-west and south-east corners;
- Maintain vegetation on centre island – there is a crest in the centre island and at the time of the site visit it was getting quite tall which obstructed the view from south approaching traffic to the other side of the intersection (approaching at significant grade);
- Investigate possibility of relocating/removing some of the 8 electricity/light poles within the clearance zone to less critical areas within the clearance zone; and
- If the advanced warning and narrowed width does not improve rear-end crashes, then a treatment such as Calcium bauxite could be considered to improve vehicle stopping distance.

4.5.10 Rank 10: SW1 – Alderley Street and Drayton Road

High entry speeds were observed during the site visit at SW1 which is one of the most likely causes of the high number of angle crashes observed at this roundabout. The high entry speeds need to be reduced by improving the entry geometry.

Some possible remedial treatments to reduce entry speed to the roundabout include:

- Reduce the entry path radius to below the maximum 55m – it was identified that the south approach has an insufficient entry path radius of 60m (this could just be measurement inaccuracy due to using aerial imagery);
- Reduce deflection radius to the maximum of 100m through the roundabout for the north approach – it was measured at 120m;
- Reduce entry width – up to the minimum of 3.0m; and
- Install reverse curves to progressively slow vehicles upon approach to the roundabout.

Some other possible remedial treatments include:

- Improve sight distance on south and east approaches by removing/reducing vegetation on south-east and north-east corners;
- Re-apply line marking throughout the roundabout to improve clarity of vehicle paths through the roundabout;
- Re-apply yellow ‘shared zone’ bicycle symbols to improve awareness of bicycles at the intersection;
- Investigate the possible removal/relocation of some of the 6 electricity/light poles within the clearance zone to a less critical area of the clearance zone; and
- To reduce rear end crashes a treatment such as Calcium bauxite could be considered to improve vehicle stopping distance.

5.0. CONCLUSIONS

The crash data analysis for all of the roundabouts in Toowoomba identified that the three most common types of crash are angle crashes (74%), hit object crashes (13%) and rear-end crashes (9%) where the remaining 4% of crashes are made up of a range of other crash types. Property damage only (PDO) crashes made up over half of the crashes at roundabouts in Toowoomba which highlights the need to continue to gather and record the data from PDO crashes to enable early identification of roundabouts performing poorly rather than having to wait for injury data to begin to show the poor performance. Cars are the most commonly involved vehicle in roundabout crashes, however, motorcycles, bicycles, trucks, pedestrians, buses and other vehicles are also represented in crashes at roundabouts in Toowoomba.

A combination of two road safety methodologies (critical crash rate method and relative severity index method) were used in the ranking of the roundabouts. The critical crash rate method considered the number of crashes with respect to traffic volume and the relative severity index method considered costs by crash type. It was found that combining these two methods using scores and weighting factors of 0.5 for each method providing a much better ranking result than the single methods on their own. It allowed for more variables to be considered rather than excluding important factors.

The final ranking of the top 10 roundabouts was:

1. SW7 – Glenvale Rd and McDougall St
2. NW6 – Anzac Ave, Russell St and West St
3. SW6 – Glenvale Rd and Greenwattle St
4. NW7 – North St and Tor St
5. SE21 – Spring St and Hume St
6. SE14 – Alderley St and Ramsay St
7. SE12 – South St and MacKenzie St
8. SE13 – Alderley St and Hume St
9. SE15 – Alderley St and MacKenzie St
10. SW1 – Alderley St and Drayton Rd

By comparing the combined scores for each roundabout it was found that only the rank of the top 5 roundabouts proved significant. After that, the ranking order changed considerably when the weighting factors for the two methods were changed. This was due to the marginal difference in scores between these roundabouts indicating that the performance for these roundabouts are relatively similar. It is suggested that future studies should only consider the top 5 worst performing roundabouts.

Road safety audits were conducted at the top 10 worst performing roundabouts and the most significant crash contributory factors that were identified were high entry speeds and reduced sight distance upon approach to the roundabout. The observed high entry speeds were most commonly associated with entry path radii that were too large as well as deflection through the roundabout greater than the maximum allowable. Sight distance due to vegetation on the corners of roundabouts was a common issue observed at the top 10 roundabouts and there were significant numbers of electricity/light poles and trees within the clearance zone of the roundabouts.

Finally, the main remedial measures proposed for the top 10 worst performing roundabouts included:

- Limiting the entry speed to the roundabout through the use of reduced entry path radii, radius of deflection, entry widths and installation of reverse curves (where applicable);
- Improving sight distance by removing or reducing vegetation on corners where the sight distance is obstructed;
- Re-apply line marking and/or bicycle ‘shared zone’ symbols that have become faded; and
- The removal or relocation of some electricity/light poles and trees within the clearance zone.

6.0. FURTHER WORK

This dissertation has identified some significant crash contributory factors at the worst performing roundabouts in Toowoomba. However, one of the main limitations that was discovered along the way was that the level of detail in the crash data did not provide enough information in regard to how the crash occurred or the exact location – whether the crash occurred in the entry, exit or carriageway of the roundabout. Linking specific geometric properties with the crash data became difficult without the more detailed crash reports which may be available upon request to TMR.

If the detailed crash reports can be obtained for the crashes at Toowoomba roundabouts, a further investigation using a regression analysis would provide some very useful findings in regard to how different geometric properties affect the safety performance of a roundabout. It would be useful to conduct this investigation when more recent crash data is available from the Department of Transport and Main Roads and the regression analysis should be conducted on all roundabouts in Toowoomba – not just the worst performing roundabouts to accurately determine the effect a particular geometric feature (or combination of features) has on the crash rate.

Another interesting investigation would be into developing crash prediction models for the roundabouts in Toowoomba and comparing the results with the program ARNDT developed by Owen Arndt. The ARNDT software uses crash prediction models that are based on the geometric features of roundabouts in Queensland.

Another area of research that could potentially be investigated is the provision for cyclists at roundabouts. It may be necessary to look further than just Toowoomba for the crash investigation to determine which cyclist treatments provide the best outcomes as the only cyclist treatments at roundabouts in Toowoomba were: yellow 'shared zone' bicycle symbols on some approaches with or without associated signage or no provision at all. Cyclists were involved in approximately 5% of crashes in Toowoomba and were over represented at some of the roundabouts such as SE15 – Alderley and MacKenzie St where it was identified that 4 out of 9 of the crashes involved bicycles.

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APPENDIX A - PROJECT SPECIFICATION

The project specification for this dissertation is included on the following page.

ENG4111/4112 Research Project

Project Specification

For: Megan Stark

Title: Road Crash Investigation and Analysis for Roundabouts in Toowoomba

Major: Civil Engineering

Supervisor: Dr. Soma Somasundaraswarun

Enrolment: ENG4111 – EXT S1, 2016
ENG4115 – EXT S2, 2016

Project Aim: The use of roundabouts is widespread in Toowoomba, the largest regional city in Australia, yet crashes at these roundabouts contribute a substantial amount to the total crashes. Therefore, the purpose of this study is to analyse the road crash data from roundabouts in Toowoomba with the aim of evaluating the safety performance at each roundabout to re-examine the geometric features of the poorer performing roundabouts that may be modified to reduce the severity or frequency of road crashes.

Programme: Issue A, 16th March 2016

1. Quantify (human, economic and social costs), characterise (type of road crash), and interpret crashes at roundabouts to identify significant contributing factors.

2. Gather or develop suitable, scientific based, road safety methodologies for further investigation and analysis of the safety of the roundabouts in Toowoomba.

3. Use several of these methodologies in conjunction with road crash data (Department of Main Roads or other appropriate sources) to identify the top 10 roundabouts that have the worse safety performance

4. Carry out a road safety audit at selected top 10 worst performing roundabouts to collect the geometric and other features that may have contributed to the crashes.

5. Investigate other contributing factors that may have contributed to the road crashes such as but not limited to; weather conditions, time of day, time of year or type of vehicle involved.

6. Propose appropriate remedial measures to improve the safety of these locations and if they prove significant then make recommendations to Austroads guidelines.

If time permits

7. Use ARNDT software (or any suitable models) to compare and correlate the geometric features that may be affecting road safety at one or more of the identified roundabouts as a case study.

APPENDIX B – ROAD SAFETY AUDIT CHECKLIST

The road safety audit checklist was used at the end of each site visit to ensure all of the road features had been considered. This checklist was adapted from the checklists outlined in Austroads Guide to Road Safety Part 6 – Road Safety Audit (Austroads 2009b).

CHECKLIST 6: EXISTING ROADS: ROAD SAFETY AUDIT – ADAPTED FOR TOOWOOMBA ROUNDABOUTS			
Issue	Yes	No	Comment
3.4.6 Roundabout Geometry			
Is adequate deflection provided to reduce approach speeds?			
If splitter islands are needed, are they adequate for sight distance, length, pedestrian storage etc.?			
Is the central island prominent?			
Are the central island details satisfactory? Delineation, mountability, conspicuousness?			
Are all intersections located safely with respect to the horizontal and vertical alignment?			
6.1.6 Widths			
Are traffic lane and carriageway widths adequate for the traffic volume and mix?			
6.3.4 Layout			
Is the intersection layout obvious to all road users?			
Is the alignment of kerbs obvious and appropriate?			
Is the alignment of traffic islands obvious and appropriate?			
Is the alignment of medians obvious and appropriate?			
Can all likely vehicle types be accommodated?			
6.12 Provision for heavy vehicles **6.12.1 Design issues**			
Is there adequate manoeuvring room for large			

vehicles along the route, at intersections, roundabouts, etc.?			
6.1 Road alignment and cross-section **6.1.1 Visibility; sight distance**			
Is sight distance adequate for the speed of traffic using the route?			
Is the sight distance appropriate for all movements and all road users?			
Is adequate sight distance provided at all private driveways and property entrances?			
Is the presence of each intersection obvious to all road users?			
Is there stopping sight distance to the rear of any queue or slow-moving turning vehicles?			
6.1.5 Readability by drivers			
Is the road free of elements that may cause confusion? For example: ▪ is alignment of the roadway clearly defined? ▪ has disused pavement (if any) been removed or treated? ▪ have old pavement markings been removed properly? ▪ do tree lines follow the road alignment? ▪ does the line of street lights or the poles follow the road alignment?			
6.4 Signs and lighting **6.4.1 Lighting**			
Has lighting been adequately provided where required?			
Is the road free of features that interrupt illumination? (for example, trees or overbridges)			
Is the road free of lighting poles that are a fixed roadside hazard?			
Are frangible or slip-base poles provided?			

Ambient lighting: if it creates special lighting needs, have these been satisfied?			
Is the lighting scheme free of confusing or misleading effects on signals or signs?			
Is the scheme free of any lighting black patches?			
6.4.2 General signs issues			
Are all necessary regulatory, warning and direction signs in place? Are they conspicuous and clear?			
Are the correct signs used for each situation, and is each sign necessary?			
Are all signs effective for all likely conditions? (for example, day, night, rain, fog, rising or setting sun, oncoming headlights, poor lighting)			
6.4.3 Sign legibility			
In daylight and darkness, are signs satisfactory regarding visibility and: ▪ clarity of message? ▪ readability/legibility at the required distance?			
Is sign retroreflectivity or illumination satisfactory?			
Are signs able to be seen without being hidden by their background or adjacent distractions?			
Is driver confusion due to too many signs avoided?			
6.4.4 Sign supports			
Are sign supports out of the clear zone?			
If not, are they: ▪ frangible? ▪ shielded by barriers (for example, guard fence, crash cushions)?			
6.5 Markings and delineation **6.5.1 General issues**			

Is the line marking and delineation: ▪ appropriate for the function of the road? ▪ consistent along the route? ▪ likely to be effective under all expected conditions? (day, night, wet, dry, fog, rising and setting sun position, oncoming headlights, etc.)			
Are direction markings in approach lanes provided where required?			
Is the pavement free of excessive markings? (for example, unnecessary turn arrows, unnecessary barrier lines, etc.)			
6.5.2 Centrelines, edgelines, lane lines			
Are centrelines, edgelines, lane lines provided? If not, do drivers have adequate guidance?			
Have RRPMs been installed where required?			
If RRPMs are installed, are they correctly placed, correct colours, in good condition?			
Is the linemarking in good condition?			
6.3.3 Controls and delineation			
Are pavement markings and intersection control signs satisfactory?			
Are vehicle paths through intersections delineated satisfactorily?			
Are all lanes properly marked (including any arrows)?			
6.6 Crash barriers and clear zones **6.6.1 Clear zones**			
Is the clear zone width traversable? (i.e. drivable)			
Is the clear zone width free of rigid fixtures? (if not, can all of these rigid fixtures be removed or shielded?)			
Are all power poles, trees, etc., at a safe distance from the traffic paths?			

Is the appropriate treatment or protection provided for any objects within the clear zone?			

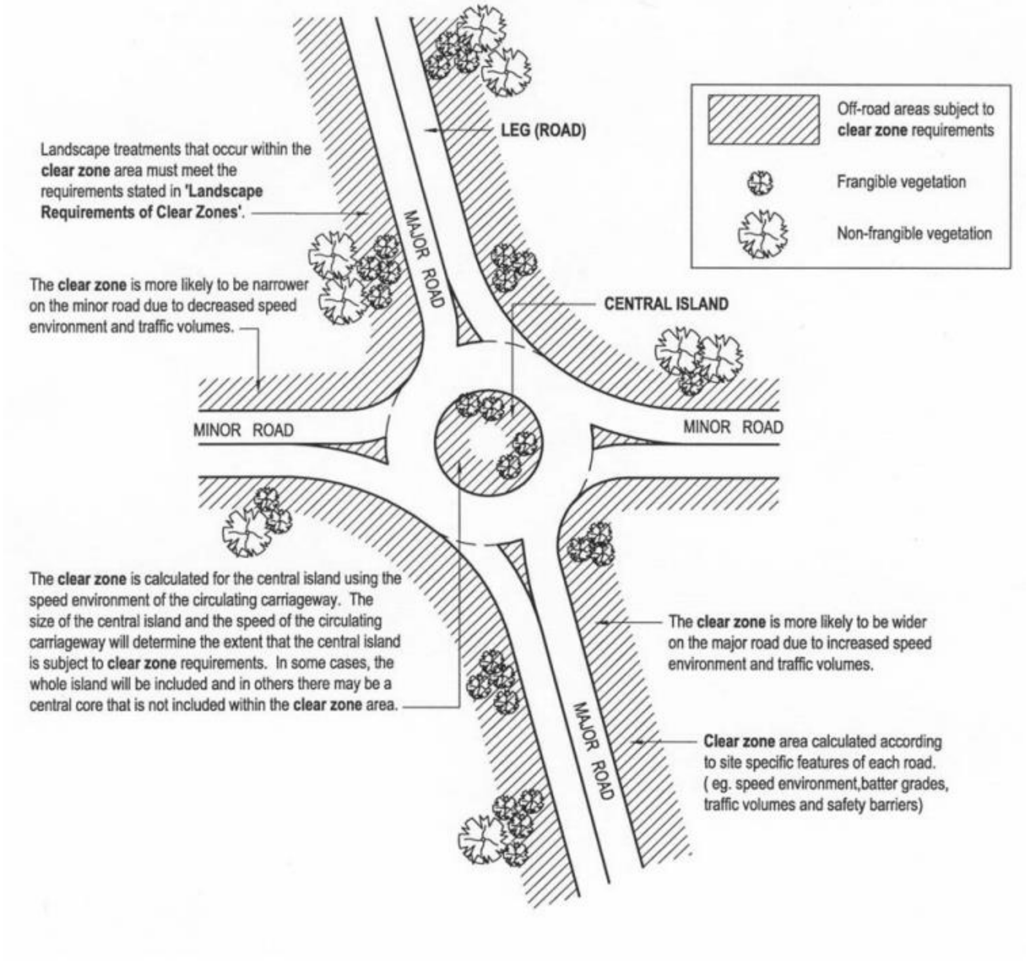

Figure C5-25: Off-road areas subject to clear zone requirements at a roundabout – Plan

Source: Main Roads 2006

6.10 Pavement **6.10.1 Pavement defects**			
Is the condition of the pavement edges satisfactory?			
Is the transition from pavement to shoulder free of dangerous edge drop offs?			
Is the pavement free of defects (for example, excessive roughness or rutting, potholes, loose material, etc.) that could			

result in safety problems (for example, loss of steering control)?			
6.10.4 Loose stones/material			
Is the pavement free of loose stones and other material?			
6.11 Parking **6.11.1 General issues**			
Are the provisions for, or restrictions on, parking satisfactory in relation to traffic safety?			
Is the frequency of parking turnover compatible with the safety of the route?			
Are parking manoeuvres along the route possible without causing safety problems? (for example, angle parking)			
Is the sight distance at intersections and along the route, unaffected by parked vehicles?			
6.8 Pedestrians and cyclists **6.8.1 General issues**			
Are there appropriate travel paths and crossing points for pedestrians and cyclists?			
Are pedestrian and bicycle facilities suitable for night use?			
6.8.2 Pedestrians			
Is there adequate separation distance between vehicular			

traffic and pedestrians on footways?			
Can pedestrians be seen by drivers in sufficient time?			
Can pedestrians determine whether vehicles are turning? (no obstructions to sight lines)			
Is there an adequate number of pedestrian crossings along the route?			
Is there adequate provision for the elderly, the disabled, children, wheelchairs and baby carriages? (for example, holding rails, kerb and median crossings, ramps)			
6.8.3 Cyclists			
Is the pavement width adequate for the number of cyclists using the route?			
Is the bicycle route continuous? (i.e. free of squeeze points or gaps)			
Are drainage pit grates bicycle safe?			
6.14 Miscellaneous **6.14.1 Landscaping**			
Is landscaping in accordance with guidelines? (for example, clearances, sight distance)			
Will existing clearances and sight distances be maintained following future plant growth?			
Does the landscaping at			

roundabouts avoid visibility problems?			
6.14.4 Roadside activities			
Are the road boundaries free of any activities that are likely to distract drivers?			
Are all advertising signs installed so that they do not constitute a hazard?			
6.14.5 Errant vehicles			
Is the roadside furniture on the verges and footways free of damage from errant vehicles that could indicate a possible problem, hazard or conflict at the site?			

APPENDIX C - USEFUL TABLES/FIGURES FROM LITERATURE

C.1 DCA Crash Codes

The DCA codes refer to Definitions for Coding Accidents and are used by the Department of Transport and Main Roads as well as Queensland police to identify crash types. The codes are defined in Figure C.1.

Figure B 3: Department of Transport and Main Roads Queensland

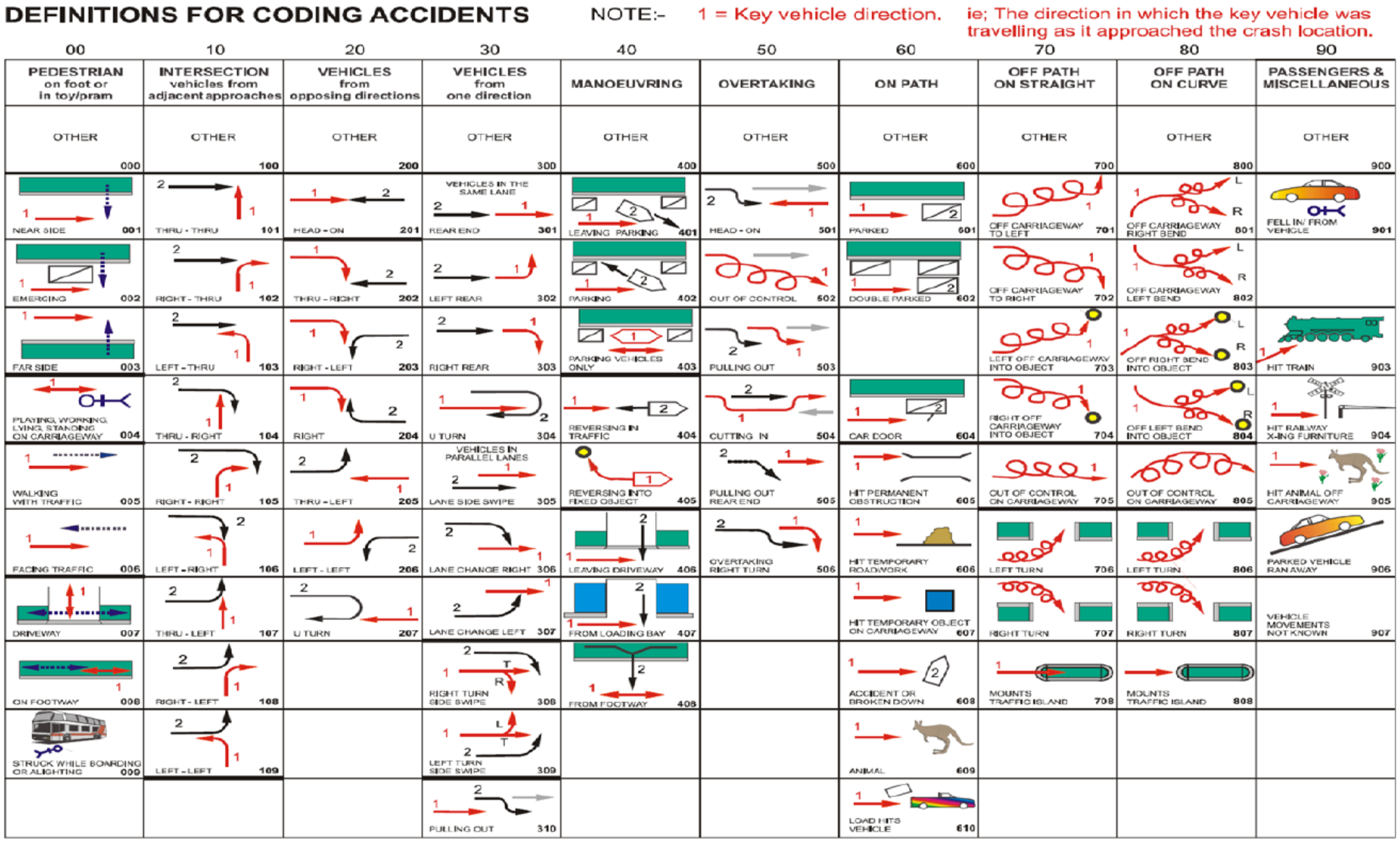

Figure C.1: DCA codes (Austroads 2015a)

C.2 Crash costs by crash type

The costs used in the relative severity index ranking method to rank the top 10 roundabouts were modified from the 2001 costs given in Austroads Guide to Road Safety Part 8: Treatment of Crash Locations which were developed by Andreassen, Figure C.2.

Guide to Road Safety Part 8: Treatment of Crash Locations

For the purpose of prioritising actions aimed at reducing crash frequency, a single average cost for all injury crashes is generally considered sufficient, particularly in view of the difficulty in predicting the specific severities of crashes that might be prevented.

The value of the crash reduction benefits is calculated using the standardised costs of particular crash types (DCA codes). Table 5.4 illustrates this information for one Australian state (Queensland). The dollar values in the table will be different in each state and territory as they are affected by the proportion of recorded crashes (by crash type) which are non-injury. This varies from jurisdiction to jurisdiction. Otherwise check with the road agency for up-to-date values applicable to the location being assessed. A method for calculating these values is given in Section 7 of Andreassen (1992a; 1992b).

Table 5.4: Example crash costs by crash type (A$)

DCA code group	DCA codes	Description	Low speed < 80 km/h $	High speed 80 km/h + $
Two vehicle crashes				
1	100–109	Intersection, from adjacent approaches	93 440	213 559
2	201, 501	Head-on	213 320	372 921
3	202–206	Opposing vehicles, turning	92 482	183 888
4	301–303	Rear-end	46 421	89 850
5	305–307, 504	Lane change	72 502	223 250
6	308, 309	Parallel lanes, turning	64 845	182 572
7	207, 304	U-turn	88 654	187 836
8	401, 406–408	Entering roadway	65 683	122 034
9	503, 505, 506	Overtaking, same direction	87 816	139 621
10	402, 404, 601, 602, 604, 608	Hit parked vehicle	65 802	147 756
11	903	Hit train	259 262	522 591
Single vehicle crashes				
12	001–009	Pedestrian	196 929	347 437
13	605	Permanent obstruction on carriageway	89 611	151 705
14	609, 905	Hit animal	48 215	53 838
15	502, 701, 702, 706, 707	Off carriageway, on straight	72 502	147 756
16	703, 704, 904	Off carriageway, on straight, hit object	139 023	251 365
17	705	Out of control, on straight	100 977	194 297
18	801, 802	Off carriageway, on curve	122 871	216 909
19	803, 804	Off carriageway, on curve, hit object	164 626	281 156
20	805, 806, 807	Out of control, on curve	104 925	143 449
Exceptions				
21	000, 200, 300, 400, 500, 600, 700, 800, 900, 901, 906, 907, 403, 405, 606, 607, 610	Crashes which are unlikely to be attributable to any road environment factor, and which are therefore unlikely to be addressed by any road-based remedial treatment. Crashes in this DCA code group will not be used in crash rates or BCR calculations or reports.		

Notes:

- *Crash costs for Queensland – estimated per crash by crash type.*
- *Costs are in 2014 dollars.*
- *Costs are based on those contained in Crash costs – 2001: costs by accident-type (Andreassen 2001), factored up by CPI and rounded to the nearest $100.*

Austroads 2015 | page 52

Figure C.2: Costs by crash type by Andreassen (Austroads 2015a)

C.3 Geometric Properties

C.3.1 Carriageway Widths

The initial selection of carriageway widths was obtained from the graph in Figure C.3.

Table 4.3: Initial selection of single-lane roundabout circulating carriageway widths

Central island radius[1] (m)	Width required for design vehicles[2] (m)				
	12.5 m single unit truck	19 m semi-trailer	25 m B-double	Type 1 road train	Type 2 road train
5	–	9.2	–	–	–
6	–	8.9	9.9	–	–
8	6.7	8.4	9.4	10.9	–
10	6.3	8.0	8.9	10.4	12.4
12	5.9	7.6	8.5	9.9	11.9
14	5.8	7.2	8.1	9.5	11.4
16	5.6	7.0	7.8	9.1	10.9
18	5.4	6.7	7.5	8.7	10.5
20	5.2	6.5	7.2	8.4	10.1
23	5.1	6.2	6.8	8.0	9.6
26	4.9	5.9	6.6	7.6	9.2
30	4.8	5.7	6.2	7.2	8.6
35	4.8	5.4	5.8	6.7	8.0
40	4.8	5.2	5.6	6.4	7.6
45	4.8	5.0	5.4	6.1	7.2
50	4.8	4.9	5.2	5.9	6.9
60	4.8	4.8	5.0	5.5	6.3
70	4.8	4.8	4.8	5.2	6.0
80	4.8	4.8	4.8	5.0	5.7

1 *Radius used for the purpose of determining vehicle path.*
2 *The widths given in this table are based on right-turning vehicle paths with a 0.5 m offset to the central island and a 0.5 m offset to the outer edge of the circulating carriageway. Widths are based on the truck turning right in the lane adjacent to the central island.*

Figure C.3: Initial selection of carriageway widths based on design vehicle (Austroads 2015b)

Table 4.4: Initial selection of two-lane roundabout circulating carriageway widths

Central island radius[1] (m)	Width required for design vehicles[2] (m) (Dual turn – design vehicle plus a car)				
	12.5 m single unit truck	19 m semi-trailer	25 m B-double	Type 1 road train	Type 2 road train
8	9.7	–	–	–	–
10	9.3	11.0	–	–	–
12	9.0	10.6	11.5	–	–
14	8.8	10.2	11.1	12.5	–
16	8.6	10.0	10.8	12.1	13.9
18	8.4	9.7	10.5	11.7	13.5
20	8.2	9.5	10.2	11.4	13.1
23	8.1	9.2	9.8	11.0	12.6
26	7.9	8.9	9.6	10.6	12.2
30	7.7	8.7	9.2	10.2	11.6
35	7.6	8.4	8.8	9.7	11.0
40	7.5	8.2	8.6	9.4	10.6
45	7.4	8.0	8.4	9.1	10.2
50	7.3	7.9	8.2	8.9	9.9
60	7.2	7.7	8.0	8.5	9.3
70	7.1	7.5	7.8	8.2	9.0
80	7.0	7.4	7.6	8.0	8.7

1 *Radius used for the purpose of determining vehicle path.*
2 *The widths in this table are nominally 3.0 m greater than the widths given for single-lane roundabouts for the reasons given in the main text.*

There are cases for which the use of the values of circulating carriageway widths in Table 4.3 and Table 4.4 may lead to inadequate entry curvature being achieved. In these cases, where it is uneconomical to increase the diameter of the central island, it is preferable to reduce the circulating carriageway widths to provide adequate entry curvature. This will result in the design vehicle having to encroach onto an over-run apron in the central island. These encroachment areas (discussed in Section 4.6.3) will need to be specially constructed and a typical cross-section is shown in Figure 4.11.

Figure C.4: Initial selection of carriageway widths for two-lane roundabout based on design vehicle (Austroads 2015b)

APPENDIX D– CRASH DATA ANALYSIS

D.1 Top 10 roundabout ranking spreadsheet

					0.5	0.5	
		Roundabouts			Crash Rate	RSI - Andreasser	Combined
1		Glenvale Road and McDougall Street	12	SW7	10.96	6.13	8.55
2		Anzac Avenue, Russell Street and West Street	27	NW6	10.16	6.41	8.29
3		Glenvale Road and Greenwattle Street	16	SW6	9.61	6.56	8.09
4		North Street and Tor Street	9	NW7	5.95	7.22	6.59
5		Spring Street and Hume Street	10	SE21	6.84	6.23	6.53
6		Alderley Street and Ramsay Street	11	SE14	5.93	6.43	6.18
7		South Street and Mackenzie Street	9	SE12	6.38	5.90	6.14
8		Alderley Street and Hume Street	15	SE13	6.36	5.86	6.11
9		Alderley Street and Mackenzie Street	9	SE15	5.66	6.37	6.02
10		Alderley Street and Drayton Road	11	SW1	5.03	6.98	6.00
		Long Street and Mackenzie Street	8	SE8	4.88	6.85	5.87
		Long Street and Hume Street	11	SE5	5.47	5.83	5.65
		Heinemann Road, Troys Road, Toowoomba-Cecil Plains Road and Carrington Road	5	NW1	5.75	5.17	5.46
		Hursley Road and McDougall Street	6	NW3	4.09	6.33	5.21
		South Street and Hume Street	6	SE10	4.05	5.31	4.68
		Stenner Street and Ramsay Street	5	SE19	2.88	6.41	4.64

Sensitivity Analysis

			70/30	60/40	50/50	40/60	30/70
12	SW7	Glenvale Road and McDougall Street	1	1	1	1	1
27	NW6	Anzac Avenue, Russell Street and West Street	2	2	2	2	2
16	SW6	Glenvale Road and Greenwattle Street	3	3	3	3	3
9	NW7	North Street and Tor Street	5	5	4	4	4
10	SE21	Spring Street and Hume Street	4	4	5	5	5
11	SE14	Alderley Street and Ramsay Street	8	8	6	6	7
9	SE12	South Street and Mackenzie Street	6	6	7	8	10
15	SE13	Alderley Street and Hume Street	7	7	8	11	11
9	SE15	Alderley Street and Mackenzie Street	9	9	9	9	9
11	SW1	Alderley Street and Drayton Road	10	10	10	7	6
8	SE8	Long Street and Mackenzie Street	13	11	11	10	8
11	SE5	Long Street and Hume Street	11	12	12	12	12
5	NW1	Heinemann Road, Troys Road, Toowoomba-Cecil Plains Road and Carrington Road	12	13	13	14	15
6	NW3	Hursley Road and McDougall Street	14	14	14	13	13
6	SE10	South Street and Hume Street	15	15	15	16	16
5	SE19	Stenner Street and Ramsay Street	16	16	16	15	14

D.2 Top 10 roundabout analysis

			CRASH INVESTIGATION														
		Leg	Angle Crashes	Rear-end Crashes	Hit Object Crashes	Other Crashes	Total Crashes	Bicycle Crashes	Motorcycle Crashes	Pedestrian Crashes	Other	Single Vehicle	Multi Vehicle	Approach Volume		Crash Rate	RSI Cost
SW7	Glenvale Road and McDougall Street		12	0	0	0	12	0	1	0	0	0	12	8948		0.424	$ 98,842
		North												2485	28%		
		South												1423	16%		
		East												2659	30%		
		West												2381	27%		
NW6	Anzac Avenue, Russell Street and West Street		19	1	4	3	27	3	1	0	5	3	24	23387		0.394	$ 103,400
		North												8650	37%		
		South												7450	32%		
		East												3536	15%		
		North-West												848	4%		
		South-West												2903	12%		
SW6	Glenvale Road and Greenwattle Street		16	0	0	0	16	2	1	0	2	0	16	10902		0.372	$ 105,783
		North												2624	24%		
		South												3334	31%		
		East												1623	15%		
		West												3321	30%		
NW7	North Street and Tor Street		8	0	0	1	9	0	2	1	0	1	8	12067		0.230	$ 116,480
		North												3235	27%		
		South												2802	23%		
		East												3207	27%		
		West												2823	23%		
SE21	Spring Street and Hume Street		9	0	0	1	10	2	1	0	0	1	10	11727		0.265	$ 100,461
		North												3292	28%		
		South												2000	17%		
		East												3026	26%		
		West												3409	29%		
SE14	Alderley Street and Ramsay Street		8	0	3	0	11	0	0	0	0	3	8	13314		0.230	$ 103,636
		North												3280	25%		
		South												3915	29%		
		East												2640	20%		
		West												3479	26%		
SE12	South Street and Mackenzie Street		9	0	0	0	9	0	0	0	0	0	9	11851		0.247	$ 95,193
		North												4631	39%		
		South												3915	33%		
		East												2083	18%		
		West												1222	10%		
SE13	Alderley Street and Hume Street		7	4	2	2	15	0	2	1	1	4	11	18082		0.246	$ 94,429
		North												4477	25%		
		South												4757	26%		
		East												4228	23%		
		West												4620	26%		
SE15	Alderley Street and Mackenzie Street		7	2	0	0	9	4	0	0	0	0	9	12074		0.219	$ 102,741
		North												3589	30%		
		South												3225	27%		
		East												2978	25%		
		West												2282	19%		
SW1	Alderley Street and Drayton Road		4	2	3	2	11	1	2	1	0	4	7	18624		0.195	$ 112,509
		North												3583	19%		
		South												4413	24%		
		East												4797	26%		
		West												5831	31%		

			ROAD SAFETY AUDIT						
		Leg	Trafficable Apron	Vegetation on centre island	Cycle Lanes / shared zone	Poles in clearance zone	Trees in clearance zone	Sight Distance to right	Linemarking condition
SW7	Glenvale Road and McDougall Street		yes	tree		8	1		Adequate
		North				2	0	Excessive	
		South				3	0	Below average	
		East			faded yellow bik	1	0	Average	
		West			yellow bike	2	0	Excessive	
NW6	Anzac Avenue, Russell Street and West Street		no	2x trees + low bushes + light pole	none	8	6		faded + cracke
		North				1	1	Average	
		South				2	1	Below average	
		East				2		Poor	
		North-West				1	1	Average	
		South-West				1	1	Below average	
SW6	Glenvale Road and Greenwattle Street		yes	tree + rocks	Glenvale Rd	4	1		Adequate
		North				1		Average	
		South	2			1		Excessive	
		East			yellow bike	1		Below average	
		West			yellow bike	1 (slip based)		Excessive	
NW7	North Street and Tor Street		yes	none	none	8	0		Adequate
		North	2			2	0	Below average	
		South				2	0	Below average	
		East				2	0	Below average	
		West				2	0	Average	
SE21	Spring Street and Hume Street		yes	tree	none	5	1		Adequate
		North	2			2	0	Average	
		South				1	0	Above average	
		East				1	0	Excessive	
		West				1	0	Below average	
SE14	Alderley Street and Ramsay Street		yes	tree	none	8	3		faded + cracke
		North	2			2	0	Average	
		South				3	1	Average	
		East				1	0	Average	
		West				2	1	Average	
SE12	South Street and Mackenzie Street		no	low plants + light pole	very faded bike symbol	6	1		faded + cracke
		North			dotted lines on entry & exit on Mackenzie St	2	0	Above average	
		South				1	0	Excessive	
		East				1	1	Poor	
		West				1	0	Excessive	
SE13	Alderley Street and Hume Street		yes	tree		7	10		Adequate
		North	2		yellow bike	2	2	Average	
		South			yellow bike	2	2	Below average	
		East			yellow bike	1	1	Average	
		West			yellow bike	2	4	Poor	
SE15	Alderley Street and Mackenzie Street		no	low vegetatio	none	8	0		Adequate
		North				1	0	Average	
		South				2		Poor	
		East				2		Below average	
		West				3		Below average	
SW1	Alderley Street and Drayton Road		no	low plants + light pole		6	1		Adequate
		North			faded yellow bik	1	0	Average	
		South			faded yellow bik	1	0	Below average	
		East			faded yellow bik	2	0	Poor	
		West			faded yellow bik	1	0	Average	

		Leg	GEOMETRIC PROPERTIES Centre Island Diameter (m)	Inscribed Circle Diameter	Circulating Roadway Width (m)	carriageway width including apron	req'd carriageway width 12.5m truck	req'd carriageway width semi	Weaving Width	Weaving Length	Approach Width	Entry Width	Exit Width	Eccentricity	Angle to Next Leg (degrees)	Deflection Radius	Approach Gradient	Absolute Gradient	Entry Path Radius
SW7	Glenvale Road and McDougall Street		14	29															
		North			7.5	9.5	7.5	9.2	7.2	16.4	3	3.4	4.5	0	90	50	-4.53	4.53	65
		South	5		7.5	9.5			7.4	15.8	5	3.7	4.3	0	90	75	4.10	4.10	65
		East			7.2	9.2			7.2	16.1	4	4.4	5.2	0	90	80	1.57	1.57	75
		West			7.6	9.6			7.2	15.7	3.8	4.5	4.8	0	90	75	-0.67	0.67	85
NW6	Anzac Avenue, Russell Street and West Street		20	31															Right Lane
		North		41	5.4	5.4			10.3	18.4	6.7	7.5	7	-4.8	82.1	130	0.28	0.28	30
		South	10		5.8	5.8			14.4	13.2	7	11	9.8	5.7	88.7	50	2.47	2.47	65
		East			10.5	10.5			11.5	19.7	4	6	6.7	4	61.5	200	2.91	2.91	75
		North-West			10.5	10.5			10.9	13.7	4.5	4.3	5.3	0	55.4	140	-2.01	2.01	70
		South-West			10.7	10.7			13.5	13.2	4.5	7.3	5.2	4.4	72.3	can't ca	-2.90	2.90	25
SW6	Glenvale Road and Greenwattle Street		12	26.8															
		North			7.5	9.5	#N/A	#N/A	7.6	14.4	4.5	3.7	4.6	0	90	50	-1.29	1.29	55
		South	4		7.2	9.2			7.2	15.6	4.3	3.5	4.2	0	90	55	1.29	1.29	50
		East			7	9			7.8	15.4	3.1	4.3	4.3	0	90	65	-5.92	5.92	85
		West			7.5	9.5			8.2	14.9	3.1	4.2	4.1	0	90	180	5.73	5.73	95
NW7	North Street and Tor Street		10	24.8															
		North			7.3	9.3	#N/A	#N/A	7	14.5	4.5	3.5	3.7	0	90	60	-1.40	1.40	45
		South	3		7.3	9.3			7.4	13.6	4.8	3.5	3.3	0	90	70	1.91	1.91	60
		East			7.9	9.9			7.5	14.5	4.7	3.3	3.4	0	90	55	3.59	3.59	55
		West			6.8	8.8			6.8	13.5	4.6	3.5	3.3	0	90	60	-4.23	4.23	45
SE21	Spring Street and Hume Street		12	26															
		North			6.7	8.7	#N/A	#N/A	11.4	13.4	7	8	4.3	0	90	60	3.25	3.25	55
		South	4		7	9			8.8	14.1	5	3.8	4.7	0	90	70	-4.98	4.98	90
		East			6.8	8.8			8.1	13.9	4.4	3.3	5.2	0	90	180	-0.45	0.45	80
		West			6.5	8.5			6.8	13.8	4.8	3.6	5.5	0	90	80	1.15	1.15	50
SE14	Alderley Street and Ramsay Street		10	24															
		North			6.7	8.7	#N/A	#N/A	7	12.6	5	3.5	3.1	0	90	65	2.80	2.80	70
		South	3		6.7	8.7			7.1	13.6	5	3	3.1	0	90	45	2.97	2.97	80
		East			7	9			7.2	12.8	4.7	3.2	3.4	0	90	60	3.23	3.23	60
		West			7	9			7.3	13.4	5.1	3.2	3	0	90	60	-5.08	5.08	70
SE12	South Street and Mackenzie Street		14	32															
		North			8.7	8.7	7.4	9.05	8.9	19.5	4.5	4.6	4.8	0	102	75	-0.63	0.63	120
		South	7		8.6	8.6			8.2	19.7	4.4	3.8	4.3	0	82	70	2.59	2.59	80
		East			8.7	8.7			9.5	16.1	4.5	3.7	4.8	0	98	65	-3.85	3.85	65
		West			9	9			8.7	16.1	4.7	3.8	4.7	0	78	60	0.00	0.00	65
SE13	Alderley Street and Hume Street		10.5	25.6															
		North			7.1	9.1	#N/A	#N/A	6.7	15.1	6.5	4.7	4.3	0	90	60	-1.50	1.50	75
		South	3.25		7.2	9.2			6.7	14.8	4.7	3	2.8	0	90	70	1.59	1.59	45
		East			7.2	9.2			6.4	13.8	4.4	3.1	3	0	90	55	-3.34	3.34	35
		West			7.3	9.3			7.3	13.7	4.9	3.4	3	0	90	50	3.39	3.39	50
SE15	Alderley Street and Mackenzie Street		10	26															
		North			7.5	7.5	7.5	9.2	7.2	15	4.8	3.5	3.5	0	90	50	-0.37	0.37	50
		South	5		7.5	7.5			7.4	13.8	4.8	3	3.3	0	90	75	0.59	0.59	55
		East			7.5	7.5			7.1	13.6	4.2	3.3	3.9	0	90	130	6.93	6.93	60
		West			7.8	7.8			7.2	14.5	4.8	3.1	3.2	1.3	90	45	-3.82	3.82	45
SW1	Alderley Street and Drayton Road		15	30															
		North			7.5	7.5	6.8	8.525	11.4	12.8	5	5.7	4.7	3.5	68.8	120	3.66	3.66	40
		South	7.5		7	7			10.5	12.6	5	4.4	4.7	2.6	87.05	40	0.88	0.88	60
		East			7	7			6.6	19.5	4.8	5	6.5	3.7	83	85	3.14	3.14	45
		West			7.9	7.9			7.4	22.7	4	4.6	5	3.7	120.8	45	-2.79	2.79	45

D.3 Excess proportion of specific crash type spreadsheet

ANGLE											
		Code	**Roundabout**	**N_obs_i**	**(N_obs_i)^2**	**N_obs_tot**	**(N_obs_tot)^2**	**N_obs/N_obs_tot**		**pi**	**p**
n	10	SW6	Glenvale Road and Greenwattle Street	16	256	16	256	1.000	1.000	1.000	0.996
p*i	0.767	NW6	Anzac Avenue, Russell Street and West Street	19	361	27	729	0.704	0.487	0.704	0.263
Var	0.038	NW7	North Street and Tor Street	8	64	9	81	0.889	0.778	0.889	0.838
AVE p*i	0.783	SW7	Glenvale Road and McDougall Street	12	144	12	144	1.000	1.000	1.000	0.988
alpha	2.753	SE21	Spring Street and Hume Street	9	81	10	100	0.900	0.800	0.900	0.869
beta	0.764	SE14	Alderley Street and Ramsay Street	8	64	11	121	0.727	0.509	0.727	0.446
		SE12	South Street and Mackenzie Street	9	81	9	81	1.000	1.000	1.000	0.973
		SW1	Alderley Street and Drayton Road	4	16	11	121	0.364	0.109	0.364	0.007
		SE15	Alderley Street and Mackenzie Street	7	49	9	81	0.778	0.583	0.778	0.589
		SE13	Alderley Street and Hume Street	7	49	15	225	0.467	0.200	0.467	0.013
				99		129		7.828	6.466	7.828	

Hit Object											
		Code	**Roundabout**	**N_obs_i**	**(N_obs_i)^2**	**N_obs_tot**	**(N_obs_tot)^2**	**N_obs/N_obs_tot**		**pi**	**p**
n	10	SW6	Glenvale Road and Greenwattle Street	0	0	16	256	0.000	0.000	0.000	0.078
p*i	0.070	NW6	Anzac Avenue, Russell Street and West Street	4	16	27	729	0.148	0.017	0.148	0.841
Var	0.004	NW7	North Street and Tor Street	0	0	9	81	0.000	0.000	0.000	0.138
AVE p*i	0.058	SW7	Glenvale Road and McDougall Street	0	0	12	144	0.000	0.000	0.000	0.108
alpha	0.685	SE21	Spring Street and Hume Street	0	0	10	100	0.000	0.000	0.000	0.127
beta	11.162	SE14	Alderley Street and Ramsay Street	3	9	11	121	0.273	0.055	0.273	0.909
		SE12	South Street and Mackenzie Street	0	0	9	81	0.000	0.000	0.000	0.138
		SW1	Alderley Street and Drayton Road	1	1	11	121	0.091	0.000	0.091	0.437
		SE15	Alderley Street and Mackenzie Street	0	0	9	81	0.000	0.000	0.000	0.138
		SE13	Alderley Street and Hume Street	1	1	15	225	0.067	0.000	0.067	0.353
				9		129		0.578	0.072	0.578	

Rear End											
		Code	**Roundabout**	**N_obs_i**	**(N_obs_i)^2**	**N_obs_tot**	**(N_obs_tot)^2**	**N_obs/N_obs_tot**		**pi**	**p**
n	10	SW6	Glenvale Road and Greenwattle Street	0	0	16	256	0.000	0.000	0.000	0.075
p*i	0.078	NW6	Anzac Avenue, Russell Street and West Street	1	1	27	729	0.037	0.000	0.037	0.168
Var	0.008	NW7	North Street and Tor Street	0	0	9	81	0.000	0.000	0.000	0.145
AVE p*i	0.080	SW7	Glenvale Road and McDougall Street	0	0	12	144	0.000	0.000	0.000	0.108
alpha	0.618	SE21	Spring Street and Hume Street	0	0	10	100	0.000	0.000	0.000	0.131
beta	7.121	SE14	Alderley Street and Ramsay Street	0	0	11	121	0.000	0.000	0.000	0.119
		SE12	South Street and Mackenzie Street	0	0	9	81	0.000	0.000	0.000	0.145
		SW1	Alderley Street and Drayton Road	3	9	11	121	0.273	0.055	0.273	0.927
		SE15	Alderley Street and Mackenzie Street	2	4	9	81	0.222	0.028	0.222	0.815
		SE13	Alderley Street and Hume Street	4	16	15	225	0.267	0.057	0.267	0.961
				10		129		0.799	0.139	0.799	

APPENDIX E – CRASH INVESTIGATION

The fatal crash at roundabout SE14, Alderley St and Ramsay St occurred during wet, foggy, daylight conditions and involved two cars. A quote from a newspaper article about the crash is shown below as well as a photo of the crash showing the foggy conditions, Figure 4.18.

"Sergeant Malcolm said the male driver's vehicle appeared to have hit the side of the roundabout first and sailed over it, not touching a rock decorating the middle. The vehicle is believed to have then smashed into the side of the woman s car, killing her and critically injuring her young daughter…" (Donaghey 2006)

A later article reported that the young daughter later died in hospital as a result of the crash and the driver of the other vehicle was being charged with 2 counts of dangerous driving resulting in death as well as driving unsupervised on a learners permit (Blackley 2006). This crash is an example of where the crash contributory factors of weather conditions and dangerous driving were the main contributing factors and the design of the road didn't really have much of an impact. This supports the decision to have adopted the cost by crash type ranking methodology rather than the cost by crash severity ranking in this study. This crash would have inappropriately ranked this roundabout much higher using the cost by crash severity when the main contributing factors were not a direct cause of the roundabout design itself.

APPENDIX F ROAD SAFETY AUDITS

The road safety audit findings for each of the roundabouts as well as accompanying photos from the site visits are in this appendix.

F.1 Rank 1: SW7 – Glenvale Road and McDougall Street

Some observations from the site visit included; vehicles appeared to enter the roundabout at relatively high speeds and yellow ‘shared zone’ bicycle markings were present on the east and west legs (Glenvale Rd) as well as signage.

SW7 roundabout had 4 legs at 90 degrees with a tree in the central island and a trafficable apron, Figure F.1.

Figure F.1: Central island for SW7 roundabout has a tree in the centre and a 2m trafficable apron

It was also identified during the site visit that there were a total of 8 power poles and light poles that were fixed structures within the intersection clearance zone as well as the tree in the centre of the roundabout. Figure F.2 identifies the poles circled in red and the tree represented by the red triangle.

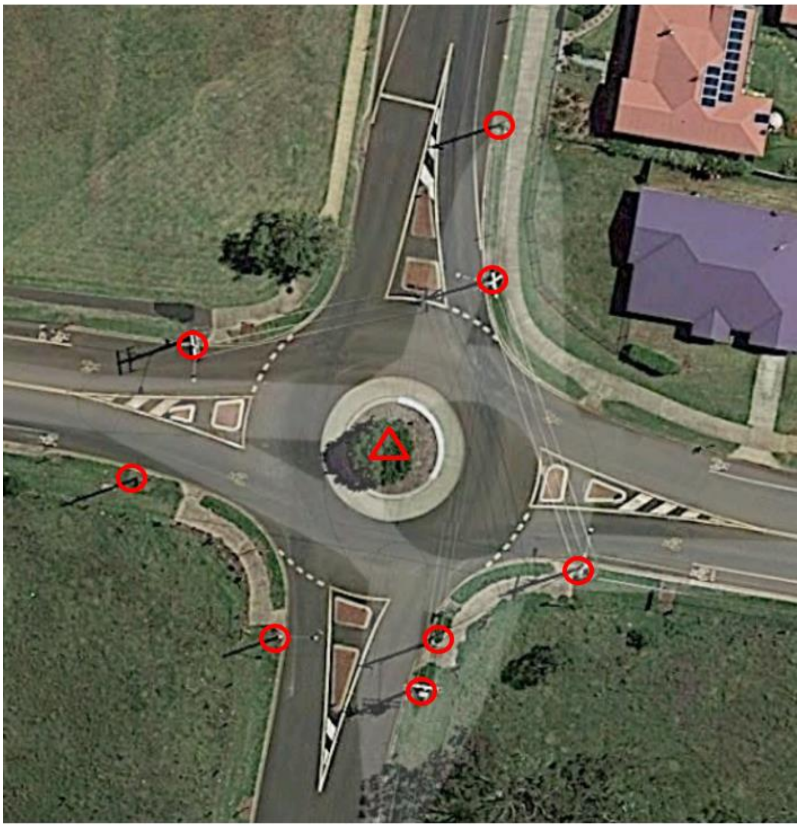

Figure F.2: Power poles, light poles and tree within clearance zone of SW7 roundabout (Google Maps 2016)

Some of the yellow ‘shared zone’ bicycle symbols are faded, Figure F.3.

Figure F.3: Faded yellow bicycle 'shared zone' symbol on the east leg of SW7 roundabout

The sight distance for the north and west approaches were considered to be excessive at this roundabout due to the vacant land on the north-west and south-west corners, see the aerial image in Figure 4.10 in section 4.4.2, allowing the approaching vehicles to see well in advance whether there is approaching traffic and allowing the traffic to enter at a higher speed. The visibility on the south and east legs were considered to be below average and average respectively. The south leg was considered to be below average due to the presence of low vegetation on the south-east and south-west corners which obstructed the view of approaching vehicles due to the uphill grade of the approach. Figure F.4, Figure F.5 and Figure F.6 show the view from this approach with approaching vehicles circled in red where only the roofs are visible. Simply ensuring regular maintenance on this vegetation would improve this sight distance.

Figure F.4: Vegetation on south west corner of SW7 roundabout

Figure F.5: Vegetation on south east corner of SW7 roundabout

Figure F.6: Vegetation on south east and south west corners of SW7 roundabout

It was noted during the site visit that for three of the pedestrian crossings the user must look around an electricity or light pole that is immediately next to the waiting area, Figure F.7 and Figure F.8. In addition to the pole there is a crest in the road on the east leg that could obstruct fast travelling vehicles from the pedestrian, Figure F.7.

Figure F.7: Pedestrian view of crest on East leg of SW7 roundabout

Figure F.8: Pedestrian crossing - power pole immediately next to crossing

A large bush on the west leg could potentially obstruct the view of approaching vehicles coming from the east leg, Figure F.9.

Figure F.9: Large bush on west leg of SW7 roundabout

F.2 Rank 2: NW6 – Anzac Avenue, Russell Street and West Street

Observations from the site visit included; vehicles appeared to enter the roundabout at relatively high speeds particularly on the north and south approaches (West St), there is no provision for cyclists at this roundabout. It was also noted during the site visit that some traffic travelling north or south through the carriageway crossed the centre line separating the two lanes of the carriageway.

The central island for NW6 roundabout has two trees, some small rocks and bushes and does not have a trafficable apron. The trees could obstruct the view of circulating traffic as they are quite dense and there are lots of low branches, Figure F.10.

Figure F.10: Central island on NW6 roundabout includes dense trees and a light pole in the centre and does not provide a trafficable apron.

The power poles, light poles and trees within the clearance zone are shown in Figure F.11. The red circles represent the power and light poles whereas the red triangles represent trees. There were 8 power and light poles identified as well as 6 trees.

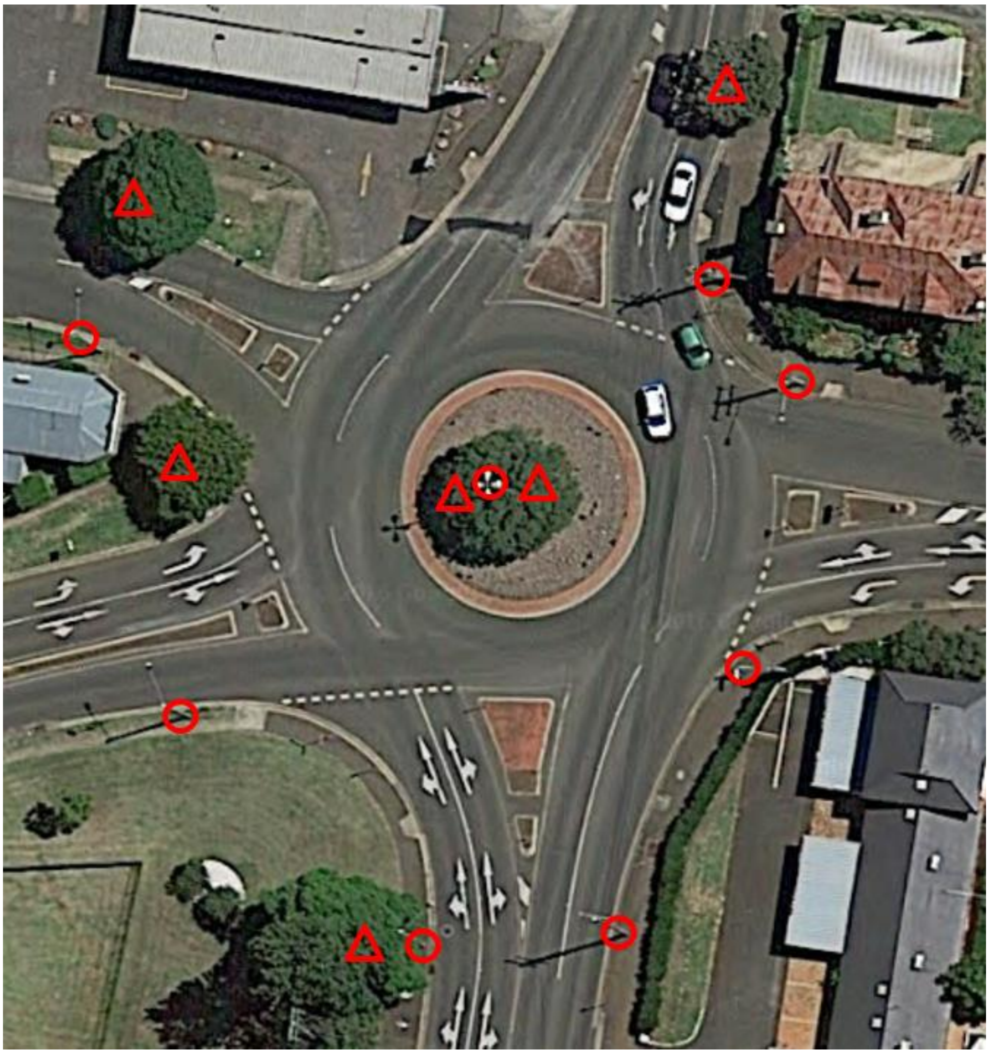

Figure F.11: Power poles and light poles at NW6 roundabout (Google Maps 2016)

There is potential that this roundabout layout could cause confusion for the road users due to its unique design. There is a sign identifying the direction of the city centre on the north approach, Figure F.12, and a sign on the east approach advising to be in the right lane for Anzac Avenue and Russell Streets, Figure F.13, though these are located at the entry to the roundabout so do not provide adequate forewarning for road users. The installation of more directional signs could improve this confusion.

Figure F.12: City centre sign on north approach at NW6 roundabout

Figure F.13: Direction sign advising to be in the right lane if requiring Anzac Ave or Russell St at NW6 roundabout

The line marking at roundabout NW6 is faded particularly around the splitter islands and the lines separating the two lanes on the entry and exit of the roundabout Figure F.14.

Figure F.14: Faded line marking at roundabout NW6

The entry to the service station is directly off the roundabout essentially adding a sixth exit to the roundabout Figure F.15.

Figure F.15: Entry to service station off roundabout at NW6

There are several trees along the very edge of the road along the north approach to the roundabout, Figure F.16.

Figure F.16: Trees lining the side of the road on the north approach of NW6 roundabout

The sight distance on the south approach was considered to be below average due to a wall and hedge on the south-east corner that could potentially obstruct vehicles approaching from the right Figure F.17.

Figure F.17: Wall and hedge on south-east corner of NW6 roundabout

There is a high fence with a hedge and other vegetation on the north-east corner that limits the sight distance of traffic approaching from the east, Figure F.18. This also obstructs the view of a pedestrian attempting to cross the east approach from this corner, Figure F.19.

Figure F.18: Sight distance from east approach at NW6 roundabout (Google Maps 2016)


Figure F.19: Sight distance from pedestrian crossing east approach at NW6

There is a significant amount of vegetation (trees and bushes) on the south west corner of the roundabout that could potentially obstruct the sight distance of vehicles approach the roundabout on the south-west leg as well as pedestrians crossing the south leg (West St), Figure F.20.

Figure F.20: Significant vegetation on the south leg of NW6 roundabout

There is potential that the sight distance for pedestrians crossing the east leg could be obstructed by parked cars, Figure F.21 shows the view of a pedestrian crossing the east approach.

Figure F.21: View of pedestrian crossing east leg of NW6 roundabout - potential that parked cars could obstruct approaching vehicles, car parks outlined in red

F.3 Rank 3: SW6 – Glenvale Road and Greenwattle Street

Some observations from the site visit at roundabout SW6 included; yellow ‘shared zone’ bicycle symbols on the east and west legs and high speeds were observed. The sight distance was considered excessive for the south and west approaches due to the vacant land on the south-east and south-west corners allowing vehicles approaching from the south or west to see any approaching vehicles well in advance and as such enter the roundabout at a higher speed. The sight distance on the north approach was considered appropriate, however the sight distance on the east approach was slightly obstructed by a fence.

The central island includes a trafficable apron, a tree in the centre as well as low rocks, Figure F.22.

Figure F.22: Central island of SW6 roundabout

The vertical geometry of this roundabout has a significant cross fall east to west across the roundabout resulting in an uphill grade travelling east through the roundabout Figure F.23.

Figure F.23: Vertical geometry of roundabout SW6 - uphill grade travelling east through roundabout

The splitter island on the north leg of the roundabout did not have a pedestrian storage area even though paths are provided for pedestrians either side of the road, Figure F.24. This leg of the roundabout is adjacent to the Glenvale convenience store so is likely to have pedestrian traffic from local residents.

Figure F.24: Missing pedestrian storage in splitter island on north leg of SW6 roundabout

The trafficable apron on the central island is almost flush with the road in some sections of the roundabout which could potentially encourage road users other than trucks to drive across the apron rather than slow down, Figure F.25.

Figure F.25: Trafficable apron on central island almost flush with road

There were 4 light and power poles and 1 tree identified within the clearance zone of the roundabout Figure F.26.

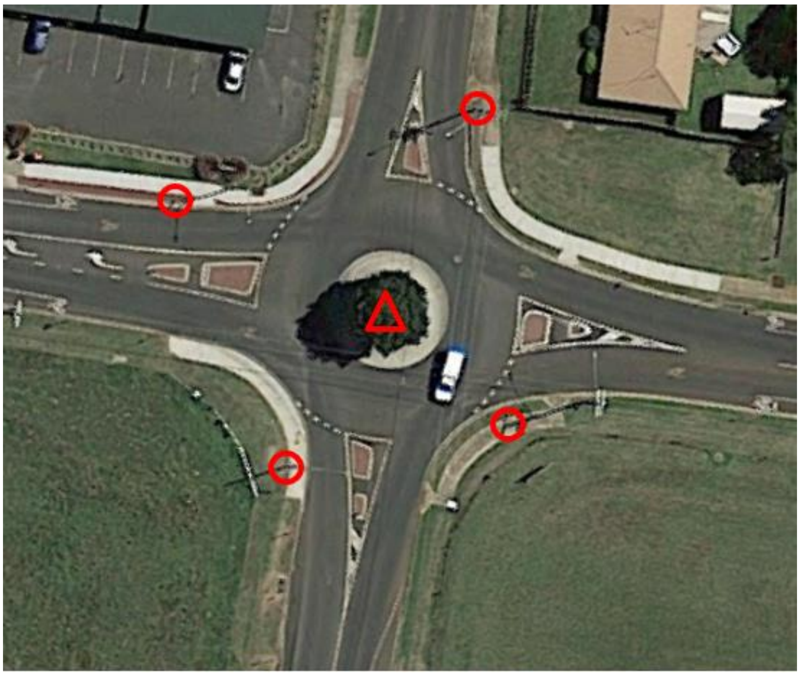

Figure F.26: Poles and trees within clearance zone of SW6 roundabout

F.4 Rank 4: NW7 – North Street and Tor Street

Some observations from the site visit to NW7 roundabout include: there is no provision for cyclists at this roundabout, there was limit of 8 tonne GVM on the east leg and high entry speeds were observed whilst on site.

The central island has a trafficable apron and does not have any features in the centre but is simply a raised circular island with signs showing the circulating direction, Figure F.27.

Figure F.27: Central island at NW7 roundabout

There were 8 light and electricity poles identified at the site investigation that were within the clearance zone, Figure F.28. It can also be seen from this figure that there is a fence and/or hedge on all of the corners except for the south-west corner. The sight distance for the north, east and west approaches was considered to be below average.

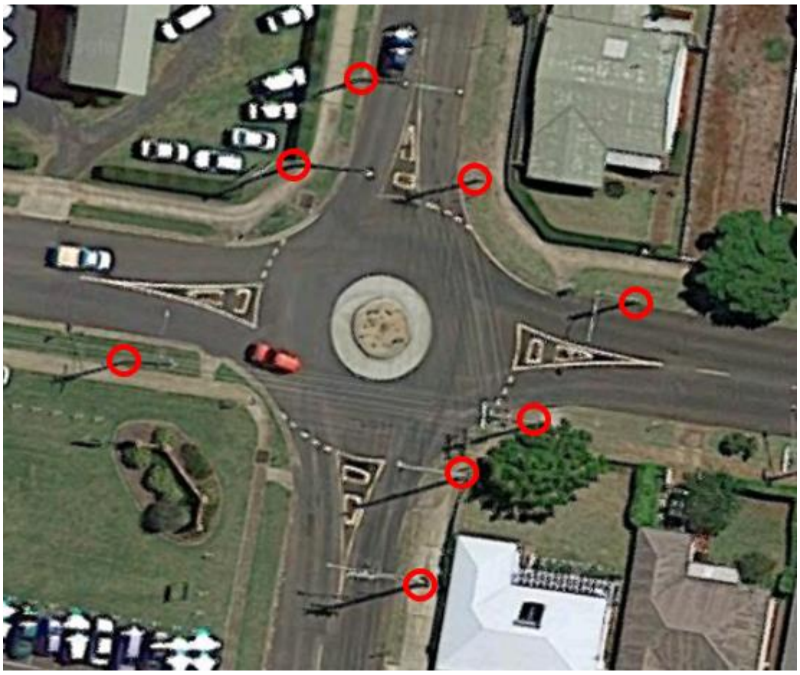

Figure F.28: Light poles and power poles at roundabout NW7

The sight distance on the east approach was considered to be below average due to the hedge on the north-east corner, Figure F.29.

Figure F.29: Sight distance from east approach on NW7 roundabout

There is a marker for a high pressure gas line located on the south-west corner of the roundabout, Figure F.30.

Figure F.30: High pressure gas main located within vicinity of NW7 roundabout

Most of the splitter islands are old and cracked, Figure F.31.

Figure F.31: Cracked splitter island at NW7 roundabout

The on street parking on Tor St may affect stopping sight distance on south approach and obstruct approaching cars from pedestrians crossing the south leg.

The power poles are installed in the centre of the pedestrian footpath on the south leg of roundabout NW7, Figure F.32.

Figure F.32: Power poles located in middle of pedestrian footpath on south leg at roundabout NW7

The no standing sign on the west approach is close to the roundabout which could have the potential to obstruct traffic flow if cars parked up the street, Figure F.33.

Figure F.33: No standing sign is located close to the roundabout

There is a vehicle limit on the east leg of the roundabout past St Andrews hospital, Figure F.34.

Figure F.34: Vehicle limit on east leg of NW7 roundabout

F.5 Rank 5: SE21 – Spring Street and Hume Street

Although not witnessed on the 11th September when the site visit was undertaken, it has previously been witnessed that during school peak times in the morning and afternoon traffic volume at this roundabout becomes very heavy due to the Christian Outreach college which has entries and exits off both the north and west legs of the roundabout and Middle Ridge State School which is further down on the east leg of the roundabout. The location of the schools also means there are school zone signs on the north and west legs.

It was also noted that the sight distance for each approach was of varying levels. The east approach was considered to have excessive sight distance and the south approach above average due to the vacant land on the north-east and south-east corners of the roundabout. The west approach however was considered to have below average sight distance due to significant vegetation in a garden on the corner.

The central island at roundabout SE21 has a trafficable apron and a tree in the centre, Figure F.35

Figure F.35: Central island at roundabout SE21

The sight distance on the west approach was considered to be below average due to the vegetation on the corner, Figure F.36. This vegetation could also potentially obstruct the sight distance of a pedestrian trying to cross the west leg.

Figure F.36: Vegetation on south-west corner of SE21 roundabout

The school zone signs on the north leg are installed behind a light post on both sides of the road which could potentially obstruct the signs, Figure F.37 and Figure F.38.

Figure F.37: School zone sign located behind light pole on north approach of SE21 roundabout


Figure F.38: School zone sign located behind light pole on north leg exit of SE21 roundabout

F.6 Rank 6: SE14 – Alderley Street and Ramsay Street

During the site investigation vehicles were observed approaching and entering the roundabout at high speeds.

The central island at SE14 roundabout has a trafficable apron with a tree in the central island, Figure F.39.

Figure F.39: Central island of SE14 roundabout

There are 8 light and electricity poles as well as three trees within the clearance zone of SE14 roundabout Figure F.40.

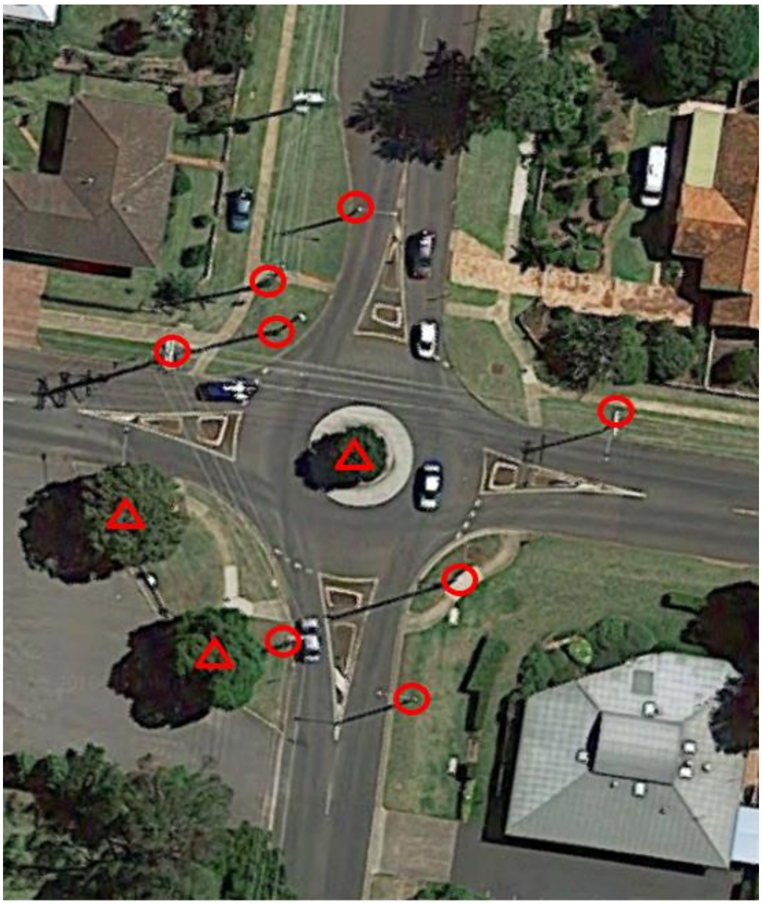

Figure F.40: Light and electricity poles and trees within clearance zone at SE14 roundabout adapted from: (Google Earth 2016)

Figure F.41: Photo of the many poles and trees within the clearance zone of the roundabout SE14

Some of the line markings are faded, Figure F.42.

Figure F.42: Faded line marking at roundabout SE14

The driveway to a residence on the north leg of the roundabout could potentially be difficult for exiting vehicles due to its proximity to the entry of the roundabout, Figure F.43.

Figure F.43: Proximity of driveway to entry to roundabout SE14 on the north leg

There is a slight crest on the south leg that can be seen on approach to the roundabout in Figure F.44 and upon exit of the roundabout in Figure F.45.

Figure F.44: Crest on south leg of SE14 on approach to the roundabout

Figure F.45: Crest on south leg of SE14 upon exit of the roundabout

F.7 Rank 7: SE12 – South Street and MacKenzie Street

During the site visit it was noted that vehicles were entering the roundabout at quite high speed. Another observation was that the roundabout is built next to the creek and had flood hazard signs suggesting it is prone to flooding in heavy rain.

The central island contains a light pole in the centre with very low vegetation and no trafficable apron, Figure F.46.

Figure F.46: Central island of SE12 roundabout

There were 6 light poles and electricity poles identified at this roundabout as well as one very large tree on the north-east corner of the roundabout, Figure F.47.

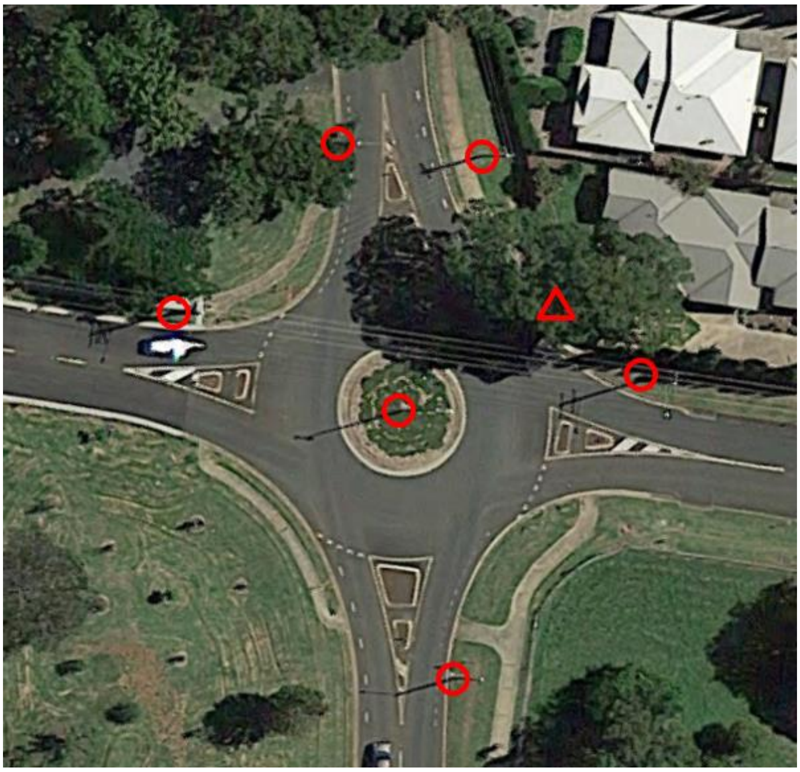

Figure F.47: Power poles, light poles and trees within the clearance zone of roundabout SE12

There are lanes on the entry and exit of the north and south legs divided by a dashed line for bicycles Figure F.48 and Figure F.49.

Figure F.48: Bicycle lanes on either side of road on north leg of SE12 roundabout

Figure F.49: Bicycle lanes on either side of road on south leg of SE12 roundabout

However, the bicycle symbols are no longer visible as they are extremely faded and there are no signs which could potentially be confusing for road users.

Figure F.50: Extremely faded bicycle symbol on SE12 roundabout

There is a very large tree on the north-east corner of the SE12 roundabout, Figure F.51. This in addition to the high fence on the corner significantly reduces the sight distance for road users travelling on the east approach.

Figure F.51: Large tree on the north-east corner of the SE12 roundabout

The line marking is faded and cracked in some places, Figure F.52, around the medians, at the give way lines and in particular the bicycle symbols indicating what the dashed lanes are on the north and south legs.

Figure F.52: Faded line marking at SE12 roundabout

F.8 Rank 8: SE13 – Alderley Street and Hume Street

It was observed during the site visit that the traffic volume at this roundabout was higher which resulted in traffic lining up at each of the legs. The site visit was conducted on a Sunday afternoon which is not a peak traffic period. It was observed that traffic was not giving way appropriately during times when the traffic volume had increased, although this could have been an independent observation not directly related to the traffic volume.

There were a total of 8 electricity and light poles identified within the clearance zone of roundabout SE13 and 7 trees, Figure F.53.

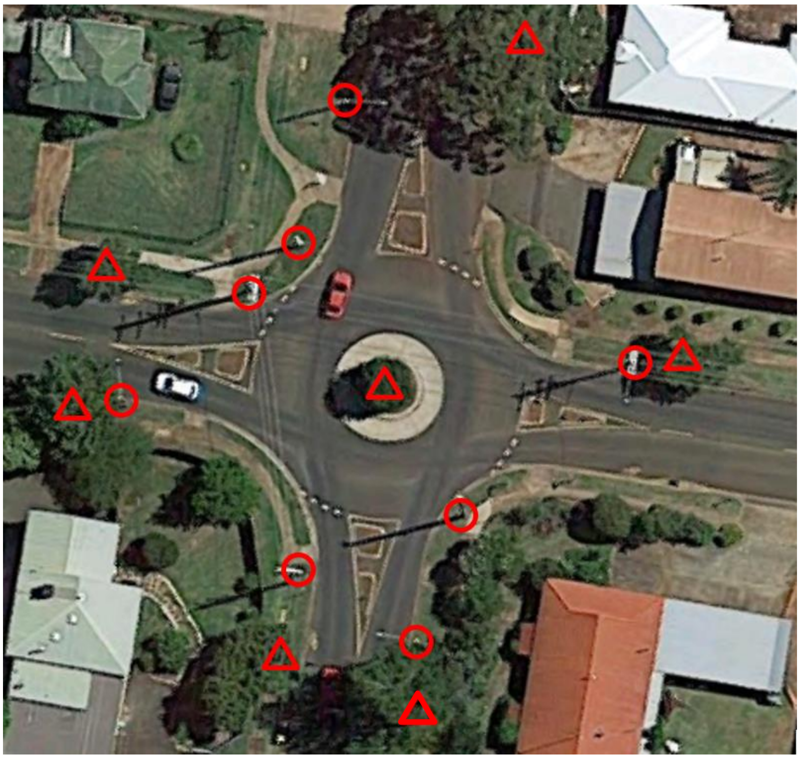

Figure F.53: Light poles, electricity poles and trees within clearance zone of roundabout SE13

The central island of SE13 roundabout has a trafficable apron and a single tree in the centre, Figure F.54.

Figure F.54: Central island of SE13 roundabout

SE13 roundabout has the third highest traffic volume out of the top 10 roundabouts. Figure F.55 shows the traffic on the south leg on a Sunday afternoon during the site visit.

Figure F.55: Traffic lining up on south approach on a Sunday afternoon

There are yellow shared zone bicycle symbols on all of the roundabout legs, Figure F.56.

Figure F.56: Yellow shared zone bicycle symbols on SE13 roundabout

The sight distance from the west approach was considered poor due to a high fence and some vegetation on the south-west corner of the roundabout, Figure F.57.

Figure F.57: Sight distance from west approach obstructed by high fence on south-west corner of SE13 roundabout

The sight distance from the south approach was considered to be below average due to vegetation on the south-east corner of the roundabout, Figure F.58.

Figure F.58: Sight distance from south approach obstructed by vegetation on south-east corner of SE13 roundabout

F.9 Rank 9: SE15 – Alderley Street and MacKenzie Street

During the road safety audits, it was observed that traffic entered the roundabout at high speeds on the north and south approaches.

The sight distance was considered to be below average on the east and west approaches due to vegetation on the north-east and south-west corners of the roundabout. The sight distance for the south approach was considered to be poor due to there being a crest upon approach to the roundabout as well as vegetation on the south-east corner of the roundabout.

The central island does not have a trafficable apron and has low vegetation in the centre of the roundabout, Figure F.59

Figure F.59: Central island at roundabout SE15

Crest in centre of roundabout as well as vegetation on central island obstructs view across roundabout between east and west approaches, Figure F.60.

Figure F.60: Crest in centre of roundabout SE15

There were 8 electricity poles and light poles and one tree which were identified as being within the clearance zone of the roundabout, Figure F.61.

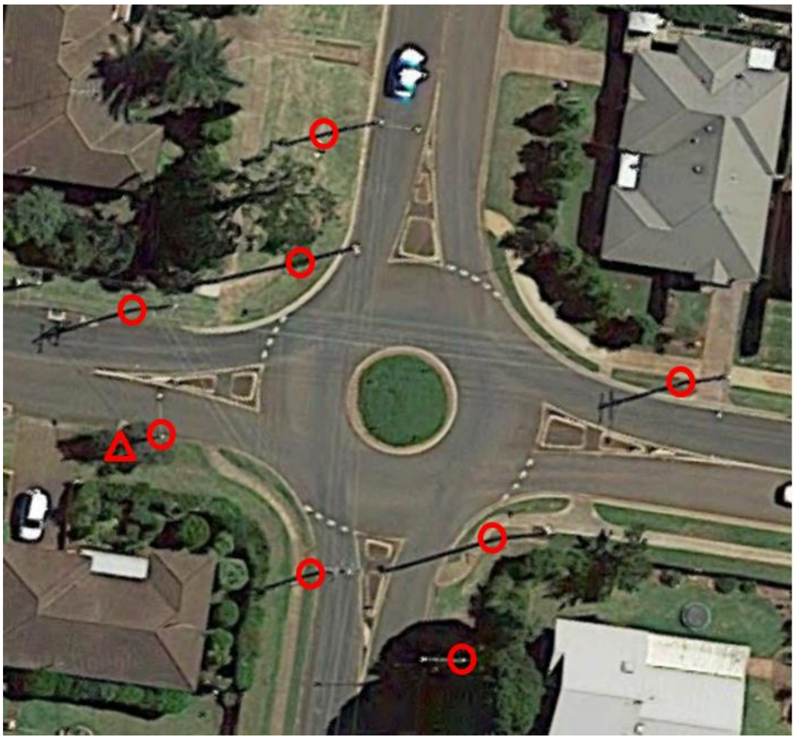

Figure F.61: Power poles, electricity poles and trees within clearance zone of roundabout SE15

The east approach to the roundabout is on a significant uphill grade which obstructs the sight distance both across the roundabout and to the right, Figure F.62.

Figure F.62: View from east approach on uphill grade at SE15 roundabout

There is a crest in the road on the south approach that could potentially obstruct the view of the upcoming roundabout, Figure F.63, where the roundabout give way sign is circled to indicate where the roundabout entry is.

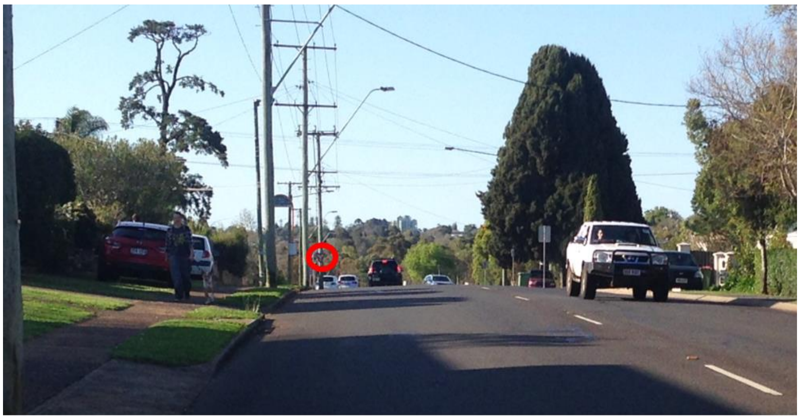

Figure F.63: Crest in road on south approach obstructing view of roundabout

The sight distance from the south approach is somewhat obstructed by the vegetation on the south-east corner of the roundabout, Figure F.64.

Figure F.64: Sight distance from south approach is obstructed due to vegetation

The sight distance on the west approach to the roundabout is also obstructed by a high fence and some vegetation, Figure F.65.

Figure F.65: Sight distance on west approach of roundabout SE15

F.10 Rank 10: SW1 – Alderley Street and Drayton Road

It was observed that the legs of this roundabout were not at 90° as is recommended.

The sight distance was considered to be below average on the south approach due to vegetation on the south-east corner of the roundabout and poor on the east approach due to dense vegetation on the north-east corner of the roundabout including a large tree.

The central island has a light pole in the centre of the island with low vegetation and some small rocks, Figure F.66. It does not have a trafficable apron.

Figure F.66: Central island of SW1 roundabout

There were 6 light poles and electricity poles and 2 trees that were identified during the site visit as being within the clearance zone, Figure F.67.

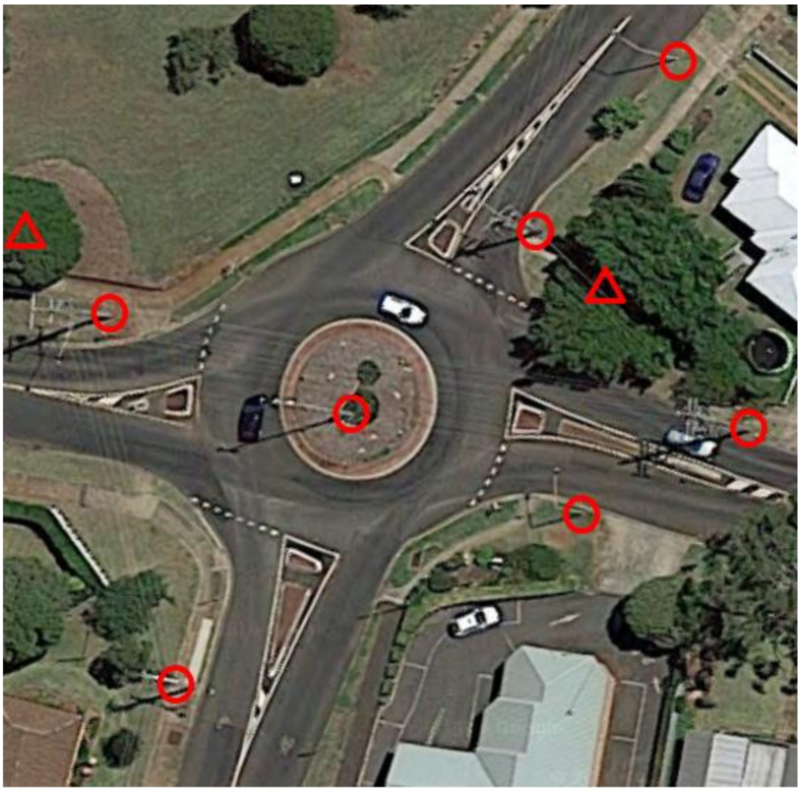

Figure F.67: Light poles, electricity poles and trees within clearance zone of roundabout SW1

The sight distance from the south approach was considered to be below average due to the vegetation and hedge on the south-east corner of the roundabout, Figure F.68.

Figure F.68: Sight distance from south approach obstructed by vegetation on south-east corner of SW1 roundabout

The sight distance from the east approach was considered poor due to the significant amount of dense vegetation and large tree on the north-east corner, Figure F.69.

Figure F.69: Sight distance from the east approach limited due to vegetation on north-east corner, (Google Maps 2016)

A photo of the vegetation on the north-east corner during the site visit, Figure F.70.

Figure F.70: Significant vegetation on north-east corner

There are yellow shared zone bicycle symbols on all four legs of the roundabout as well as signs advising road users to provide the minimum spacing from a cyclist, Figure F.71. The yellow bicycle line markings are becoming faded.

Figure F.71: Yellow shared zone bicycle symbol on road and shared zone sign at SW1 roundabout

Some of the line marking is becoming faded, Figure F.72.

Figure F.72: Faded line marking at SW1 roundabout