University of Southern Queensland

Faculty of Health, Engineering and Science

Improved theory for the design of high-speed roundabouts to suit heavy vehicles

A dissertation Submitted by

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Abstract

All roundabouts are effectively a series of "reverse curves" that vehicles are required to negotiate. These curves limit the speeds that can be achieved by vehicles through the roundabout, which is the predominant reason that this form of intersection control is often considered the safest. However, there are significant differences between the performance and capabilities of cars and heavy vehicles. This research project investigates the differences in roundabout geometry required to safely cater for heavy vehicles as well as cars, and aims to improve the design standards and guidance for designers of such roundabouts.

Roundabout usage as a form of intersection control is becoming more common every day, and they are increasingly being used in high speed areas on major roads, with a wide variety of traffic composition, including heavy vehicles. This is in contrast to their more traditional usage in low speed urban environments, which the commonly available standards and guidelines currently reflect. It is important that roundabout designers understand the differences between truck and car capabilities if they are to ensure safe and effective geometry for both vehicle types.

A case study of an actual roundabout with perceived heavy vehicle issues is carried out. An as-constructed 3D model of the roundabout is obtained, speed data collected and analysis of car vs truck speeds performed. The travelled path of a semi-trailer through the roundabout is analysed via video, and simulated using Autoturn software. 12D road design software is then used to model and measure the actual radii and crossfalls that the vehicle encountered. Combined with the speed data, the side friction being generated by the vehicles and the rate of rotation of crossfalls is then calculated and compared to relevant design standards.

An in-depth critical review of the current roundabout standards, national and international, is also carried out, and tested against known heavy-vehicle specific requirements. It is found that cars can tolerate a much higher value of side friction at roundabouts than trucks. Additionally, a cars margin for error re side friction is much higher than a trucks, ie, if a car generates side friction in excess of what it can tolerate, it will typically slide, whereas a truck will typically roll. Therefore, trucks need to negotiate roundabouts at significantly lower speeds than cars, and unique geometric considerations need to be made to facilitate this. A supplementary set of standards is developed, combining recommend combinations of geometry, signage, and linemarking to safely cater for heavy vehicles at roundabouts, and the recommendations are tested and confirmed as successful using TMR's A Roundabout Numerical Design Tool (ARNDT)

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analysis 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.

[redacted]

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University of Southern Queensland

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List of abbreviations

AGRD – Austroads Guide to Road Design

DTMR-QLD – Department of Transport and Main Roads Queensland

MRWA – Main Roads Western Australia

RMS-NSW – Roads and Maritime Services New South Wales

MUTCD – Manual of Uniform Traffic Control Devices

LOS – Level of Service

UK – United Kingdom

USA – United States of America

ARRB – Australian Road Research Board

RB1 – Roundabout 1

RB2 – Roundabout 2

HCoG – High Centre of Gravity

LTR – Load Transfer Ratio

ARNDT – A Roundabout Numerical Design Tool (also refers to its creator, Owen Arndt)

HV – Heavy Vehicle

VAS – Vehicle Activated Sign

SSD – Stopping Sight Distance

f = coefficient of side friction factor

Chapter 1 - Introduction & Background

1.1 Roundabouts – A brief history

Modern roundabouts are commonplace for road users all over Australia, and indeed the world; but where, why, and how did they originate?

According to "Roundabouts: An informational guide" (Robinson et al. 2000) roundabouts began as "traffic circles". Figure 1 depicts the first known such intersection, dubbed the "Columbus Circle", designed by William Phelps Eno, and opened in 1905 in New York City.

Figure 1 – First known roundabout "Columbus Circle"
Source: (Geo. P. Hall & Son c1907)

The original traffic circles gave priority to entering vehicles, facilitating high-speed entries; however, they soon fell out of favour due to high numbers of crashes. Circulating vehicles were also required to give-way to entering vehicles, resulting in high congestion rates.

The modern roundabout as we know it today, was developed in the United Kingdom in the mid-1960's. In 1966, the UK road and traffic authorities implemented a compulsory "give-way" traffic rule at all existing circular intersections, requiring that all entering traffic give-way to circulating traffic already on the roundabout. This eased the congestion issues, as it did not allow a vehicle to enter the intersection until there was a sufficient gap in the circulating traffic. Additionally, geometric standards that introduced horizontal curvature prior to the roundabout, known as the entry curve, were adopted, which reduced approach speeds and subsequently resulted in fewer crashes. The entry curve and other typical geometric elements of a roundabout are shown in Figure 2.

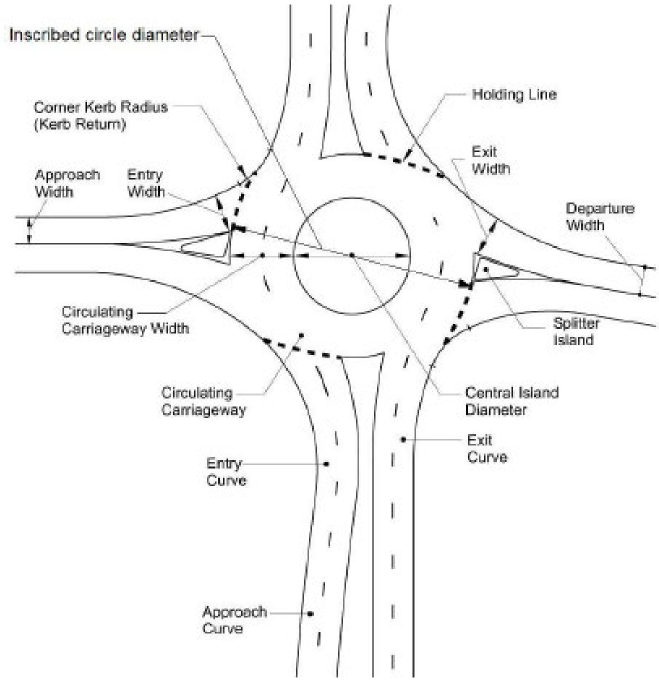


Figure 2 – Geometric Elements of a Roundabout

Source: Austroads (2015a), Figure 2.1

1.2 Roundabouts from a traffic efficiency perspective

In Australia, intersection efficiency is defined by Level Of Service (LOS), which is a function of traffic volume, density, and speed (Austroads 2015b). High LOS is achieved by those intersections that provide uncongested free flow conditions, and low LOS is produced by those intersections where the traffic flow conditions can be described as unstable and congested. Figure 3 shows the density and occupancy Level of Service indicators.

Density pc/km/lane[(1)]	Per cent occupancy[(2)]	Level of service	Flow conditions	
0–7	0–5	A	Free flow operations	Uncongested flow conditions
7–11	5–7	B	Reasonably free flow operations	
11–16	7–11	C	Stable operations	
16–22	11–14	D	Bordering on unstable operations	
22–28	14–19	E	Extremely unstable flow operations	Near capacity flow conditions
28–54	19–36	F	Forced or breakdown operations	Congested flow conditions
> 54	> 36		Incident situation operations	

1 *Density in passenger car equivalents per kilometre per lane.*

2 *Assuming* $\overline{L_V} + L_D = 6.7$ *m.*

Figure 3 – Density and occupancy Level of Service indicators

Source: Austroads (2015b), Table 7.1

For road environments with low-to-moderate traffic demand, unsignalised roundabouts generally provide a higher LOS compared to other forms of unsignalised at-grade intersections.

Roundabouts can be particularly useful where there is a high proportion of right-turning traffic. Unsignalised roundabouts perform best when the traffic flows on each approach leg are balanced, however signalisation can be utilised to help manage dominant flows on one or more approaches.

The reason that roundabouts perform efficiently under the above-mentioned conditions is due to the Australian and New Zealand practice for roundabouts to operate under the headway acceptance theory, which is defined as traffic entering the roundabout giving way to, and accepting gaps in the circulating traffic stream (Austroads 2015b). The different flow types, involving circulating, entry and exiting flow, at a typical roundabout are shown in

Figure 4.

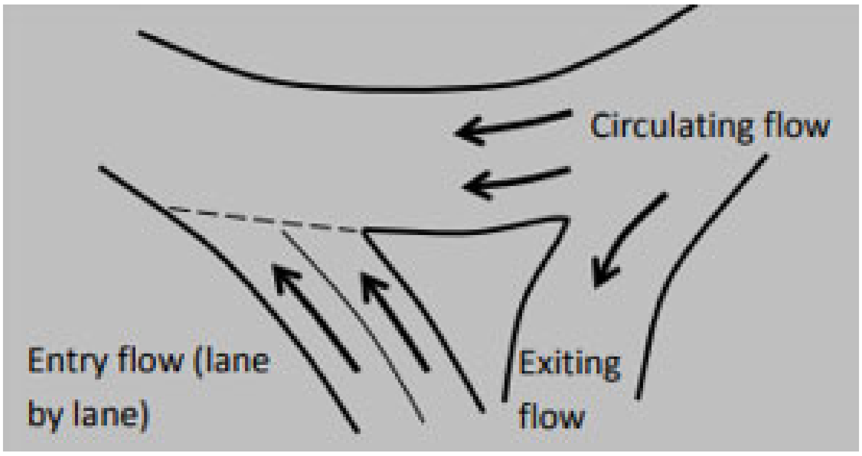


Figure 4 – Major and Minor Flows at a roundabout

Source: Austroads (2017a), Figure 6.6

1.3 Roundabouts from a safety perspective

It is widely acknowledged in the road design and traffic management industry that "a well-designed roundabout is the safest form of intersection control" (Austroads 2015a). As mentioned in the Austroads guide, numerous "before and after" type studies have shown that, in general, there are fewer vehicle crashes at well-designed roundabouts, compared to other types of intersections utilising control measures such as traffic signals, stop signs and give way signs. The exception to the above however, is the safety performance of roundabouts and their interaction with pedestrians and cyclists.

The nature of modern roundabouts, with adequate approach geometry, and the afore-mentioned "give-way" rule for entering traffic, effectively results in lower vehicle speeds compared to other types of intersections, and this is the primary reason for the improved safety record of roundabouts.

The safety performance as described above is more often associated with lower speed environments in urban areas. In such environments, as opposed to high-speed rural environments, the influence on safety of design elements such as pavement crossfall and vertical geometry are not as sensitive, and it is the purpose of this dissertation to prove that there are additional critical factors to be considered in the design of high-speed roundabouts, particularly those where a large percentage of the traffic is heavy vehicles.

1.4 Low-speed vs High-speed roundabouts

In Australia, "high speed" roundabouts are generally considered to be those with posted approach speeds of 70 kilometres per hour (km/h) (80 km/h design speed) and above. It is recommended that at this speed reverse approach curves are to be implemented on the roundabout approach, to minimise the speed at which vehicles enter the roundabouts circulating carriageway.

All roundabouts require approach vehicles to decrease their speed prior to entering the circulating carriageway. This is due to the limitations on the speed that can be travelled by a right-turning vehicle navigating the central island radius of the roundabout, which in turn is limited in size due to the practicalities of available space and construction costs.

The desirable maximum decrease in speed between the entry curve and a right-turn on the circulating carriageway is 20km/h, with the absolute maximum decrease being 30km/h (Austroads 2015a). Use of the desirable values will generally produce lower overall crash rates than the absolute values will.

In order to prevent an excessive decrease in speed at the start of the entry curve, "reverse curves" are typically used at large high-speed roundabouts, to gradually reduce the speed of vehicles. Curve radii are selected that limit the speed decrease to 20km/h between successive curves, as depicted in Figure 5.

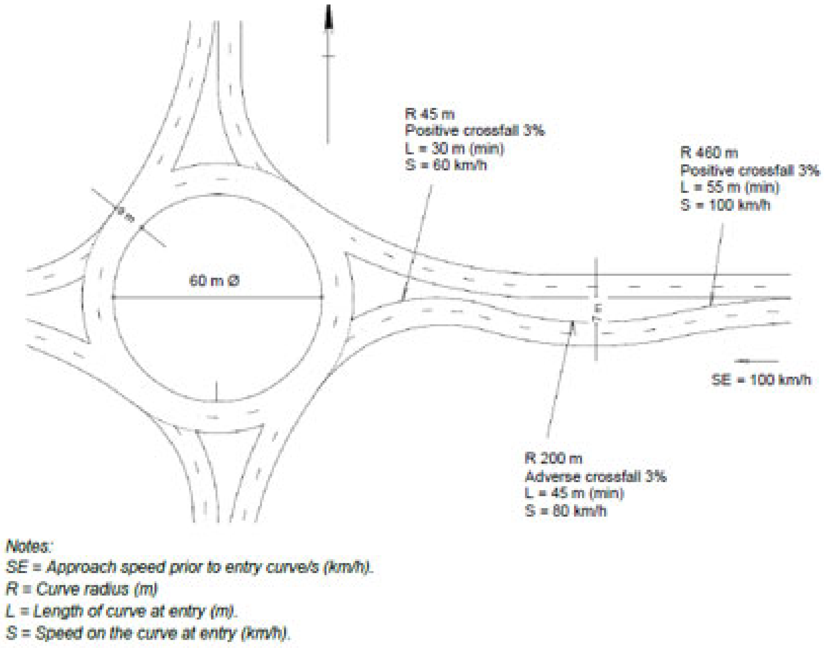


Figure 5 – Example high speed roundabout with reverse curves
Source: Austroads (2015a), Figure 4.4

It is when reverse curves are implemented that an increase in single vehicle crashes becomes more prominent at roundabouts, as opposed to multi-vehicle crashes.

The reasons for this are:

- Limited time for drivers to react to successive curves, resulting in sudden steering movements, leading to vehicle instability if the short horizontal straights are not implemented between each curve
- Insufficient deceleration lengths if the curves are not of sufficient length
- Increase in vehicle instability, particularly heavy vehicles, if the curves are super-elevated, and the super-elevations are not properly transitioned

1.5 Heavy Vehicles and roundabouts

Heavy vehicles, particularly articulated heavy vehicles, as commonly found on Australian highways, require a higher driver work-load than other smaller, non-articulated vehicles. This is due to the tracking of the trailers when negotiating curves, requiring longer and wider areas for the drivers to steer the vehicles from one direction to another. Two typical articulated heavy vehicles; a 19m Semi-Trailer and 25m B-Double are shown below in Figure 6.

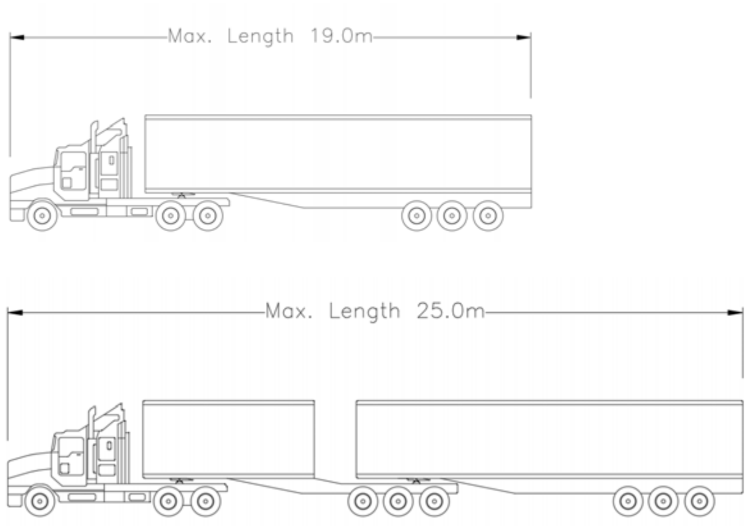


Figure 6 – Typical 19m Semi-Trailer & Typical 25m B-Double
Source: AutoTURN-Pro (2018)

Furthermore, heavy vehicles are inherently less stable than light vehicles. Figure 7 tabulates the desirable and absolute maximum values of side friction for cars and trucks. Side friction (f) is a measure of the frictional force between the pavement surface and the vehicle tyre, and the tabulated values are the maximum values to be used in design before drivers will experience discomfort. As shown below in Figure 7, the values at which heavy vehicle drivers experience discomfort is lower than that of cars, and ARRB research shows that the least stable vehicles may roll over at side friction values as high as 0.35.

Operating speed (km/h)	*f*			
	Cars		Trucks	
	Des max	Abs max	Des max	Abs max
40	0.30	0.35	0.21	–
50	0.30	0.35	0.21	0.25
60	0.24	0.33	0.17	0.24
70	0.19	0.31	0.14	0.23
80	0.16	0.26	0.13	0.20
90	0.13	0.20	0.12	0.15
100	0.12	0.16	0.12	0.12
110	0.12	0.12	0.12	0.12
120	0.11	0.11	0.11	0.11
130	0.11	0.11	0.11	–

Note: ARRB research into the stability of high centre of gravity articulated vehicles indicated that the least stable vehicles may roll over at side friction values as high as 0.35 (Mai & Sweatman 1984).

Figure 7 – Recommended side friction factors for cars and trucks

Source: Austroads (2016), Table 7.5

1.6 Austroads Vehicle Classifications

Throughout this dissertation, vehicle types are referred to in alignment with the Austroads classification system. Figure 8 below shows the 12 different vehicle classifications. In accordance with the Austroads classification system, heavy vehicles are considered those greater than Class 3.

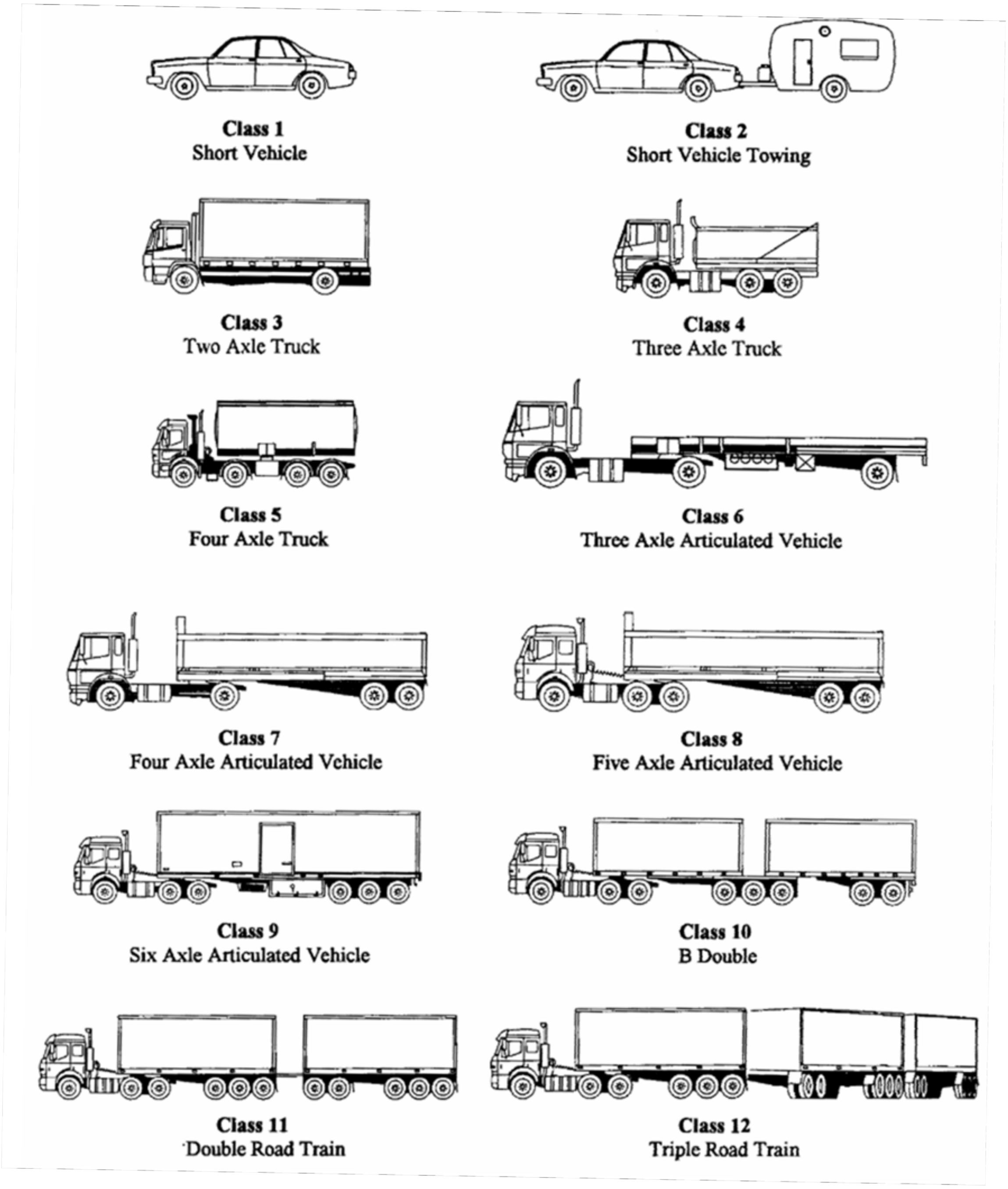


Figure 8 – Austroads Vehicle Classification

Source: Austroads (2018), Appendix B

1.7 Problem Statement

1.7.1 General

The problem in general is that there is insufficient clear and comprehensive guidance in the current Australian road design standards regarding the required standards for safe operation of high-speed roundabouts by heavy vehicles.

The guidance relies upon the mantra that roundabouts are "the safest form of intersection control", and is focused on the design elements that contribute to intersection control, for example, the interaction of vehicles with each other when negotiating roundabouts. This is acceptable for the most common form of roundabouts, such as in low-speed, urban environments, however it is potentially hazardous for high-speed areas, where more focus is required on the horizontal and vertical geometry considerations to minimise single vehicle crashes.

In the case of the Austroads Guide to Road Design publications, it can be argued that all necessary and relevant heavy vehicle standards and criteria are provided in the various chapters, and that a competent designer is able to locate and use best judgement to apply the concepts to roundabout design. However, as is shown by this dissertation, the guidance appears to be inadequately collated, referenced and integrated into the roundabout chapter, lacking specific examples and combinations of how the unique heavy vehicle criteria should be applied to roundabout design.

Specifically, the areas that require further investigation, analysis, and documentation, are detailed below in sections 1.7.2 to 1.7.6.

1.7.2 Approach Reverse Curve Geometry

The primary document for Australian roundabout design standards, Austroads (2015a), outlines the general intention of reverse curve geometry, provides brief guidance on when to use them, and warns designers of some of the negative elements, however does not provide recommended combinations of radii, super-elevation, and separating tangent lengths to suit heavy-vehicle operation.

The document does not give specific roundabout approach advice, and/or clear details on the unique scenario of using reverse curves as a speed reduction device.

1.7.3 Circulating Carriageway Crossfall

The circulating carriageway of a roundabout may feature super-elevation (crossfall towards the centre of the roundabout). In this instance, the crossfall grades in the same direction as the turning vehicle, for example, the crossfall is grading to the right, and the vehicle is turning to the right. Therefore, the crossfall acts in the opposite direction to the centrifugal forces acting on the vehicle, and the cross fall contributes to the vehicles stability on the curve.

Alternatively, a roundabout may feature adverse crossfall in the opposite direction to the turning vehicle. In this instance, the crossfall does not contribute to the stability of the vehicle as it negotiates the curve.

There are advantages and disadvantages to each method, however the current standards do not clarify in sufficient detail what these pros and cons are, and do not sufficiently highlight the consequences of choosing incorrectly, particularly in relation to heavy vehicles.

1.7.4 Rate of Rotation

The current standard outlines the general intention of reverse curve geometry, gives brief guidance on when to use them, and vaguely warns designers of some of the pit-falls, however stops short of providing recommended combinations of radii, super-elevation, and separating tangent lengths.

1.7.5 Side Friction

The Austroads (2015a) guidance does not go into sufficient detail on the maximum side-friction values to be adopted, and does not sufficiently highlight the consequences of road geometry that generates excessive side-friction demand, particularly in relation to heavy vehicles.

1.7.6 Problem Example – Case Study Introduction – RB1 and RB2

Two recently designed and constructed roundabouts on a major highway exemplify the problems described above. These roundabouts, shown below in Figure 9 and Figure 10, will be investigated and analysed as case-studies in this dissertation.

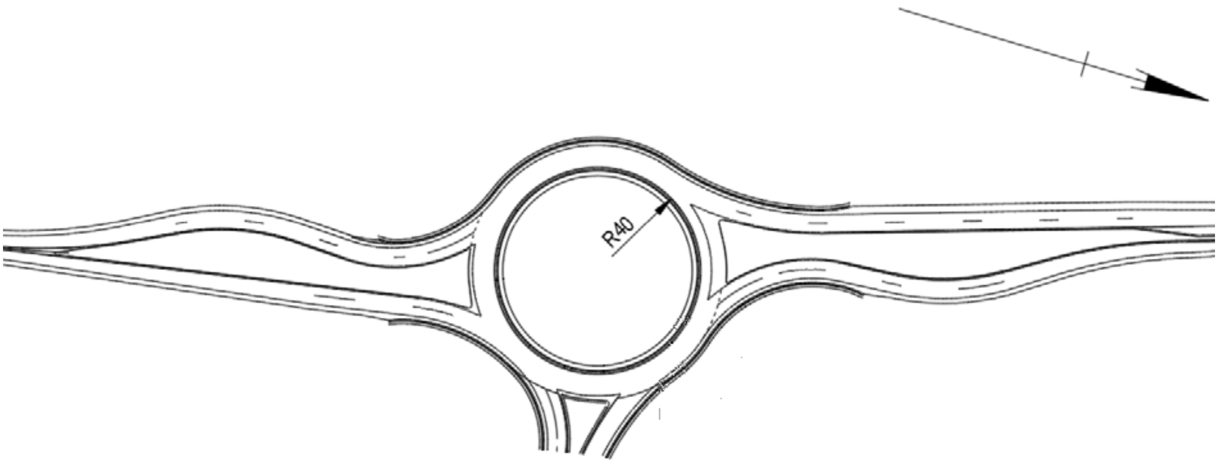


Figure 9 – Roundabout 1 (RB1)
Source: Road Authority

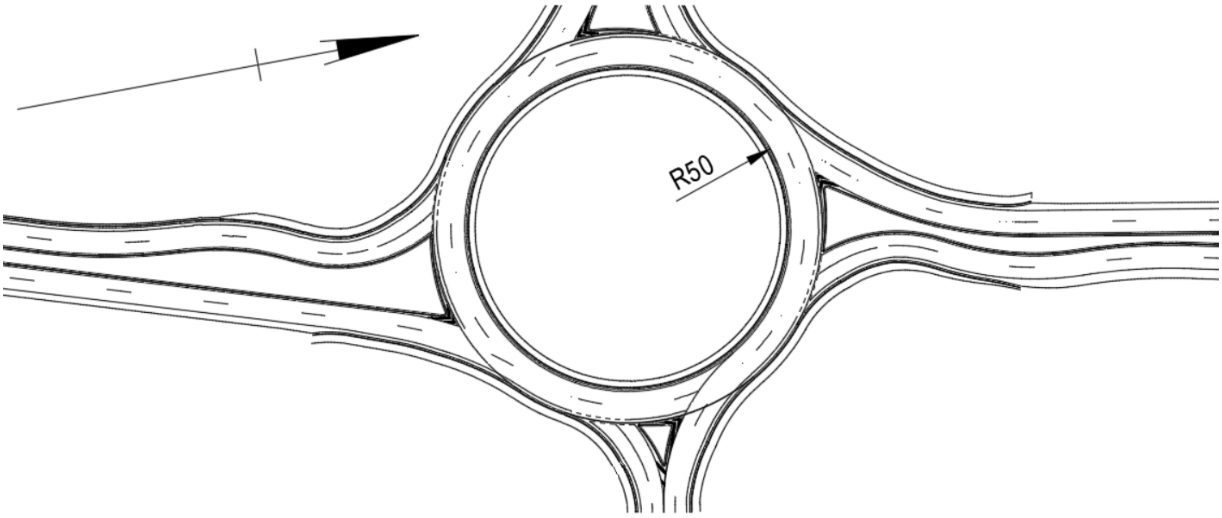


Figure 10 – Roundabout 2 (RB2)
Source: Road Authority

Both roundabouts feature:

- 80km/h posted speeds on the approach legs
- Reverse curve approach geometry
- Large radius, super-elevated circulating carriageways
- B-Double heavy vehicles
- Both have had several instances of heavy vehicle rollovers (single vehicle)

Experienced senior road designers at the relevant Road Authority have developed the roundabouts in question using the relevant afore-mentioned AGRD and relevant Road Authority supplement design guidelines, and the roundabouts underwent comprehensive design reviews prior to approval and construction.

In operation however, the roundabouts have not performed satisfactorily for heavy vehicles, with three crashes having transpired at RB1, and two crashes at RB2, over a 5 year period.

An initial review of the crashes, and subsequent assessment of the roundabout geometry, has revealed the following perceived problems, common to both roundabouts:

- Approach geometry featuring insufficiently sized horizontal curve radii, resulting in excessive side-friction demand for heavy vehicles, which can cause rollovers in the least stable vehicles
- Lack of / or insufficient length horizontal straights between reverse curves, namely between the last reverse curve just prior to the circulating carriageway (entry curve), and the circulating carriageway

- Incorrectly applied super-elevation transitions, resulting in excessive rate-rotation values, amplifying instability in the heavy vehicles
- Super-elevated circulating carriageway. In this initial review, it is perceived that the design unnecessarily incorporates super-elevation, ie crossfall to the inside of the roundabout, on the circulating carriageway. This, combined with the lack of tangent between the approach reverse curve, has produced a scenario that has proven difficult to correctly apply the necessary super-elevation transition, and has resulted in a "diagonal crown", ie an almost instant super-elevation transition from -3% to 3%, as the vehicles enter the circulating carriageway.

RB2 has undergone a review and amendment by the Road Authority following the crashes, which were considered by the Road Authority to be attributed to excessive speed by heavy vehicles. As part of the review, speed surveys were undertaken prior to and following the amendments. The speed surveys, and the Road Authority's assessment of the roundabout will be further investigated in this dissertation.

1.8 Aims and Objectives

1.8.1 Overall Aims

In Australia, particularly in lower speed environments where the design vehicle is a light vehicle, roundabouts are a commonplace form of intersection control, and the relevant geometric design standards reflect this. In higher speed environments however, and/or those with significant heavy vehicle usage, the standards appear to be relatively inadequate.

Therefore, the overall aims of this dissertation are to:

- Analyse and evaluate the commonly available standards and guidelines for high-speed roundabouts
- Identify where improvement in the standards may be required
- Develop a document that clearly and comprehensively details the design standards and guidelines specifically catering to heavy vehicles on high speed roundabouts, in the format of a supplement to current Austroads Guide to Road Design (AGRD) standards.

1.8.2 Objectives

The objectives required to achieve the above-mentioned aims are:

1. Investigate, research and understand the unique geometric requirements necessary for safe operation of high-speed roundabouts by heavy vehicles
2. Identify, develop and collate examples of best-practise combinations of geometric elements to suit high speed roundabouts
3. Collect and document recommended geometric combinations
4. Produce a document that clearly and comprehensively details the design standards and guidelines specifically catering to heavy vehicles on high speed roundabouts, in the format of an appendix to current AGRD Design Standards.
5. Using tools and software such as AutoTURN vehicle analysis and 12D Road Design software, analyse the perceived issues with RB1 (As per Section 1.7.6 Case Study Introduction), including:
    a. Crash History Analysis
    b. Speed Survey Analysis (including carrying out a speed survey using various physical methods on site)
    c. Analyse rate of rotation
    d. Analyse coefficients of side friction
    e. Develop mitigating treatment recommendations
6. Analyse the original perceived issues and confirmed successful amendments to RB2, to determine if learnings from RB2 can and/or should be implemented at RB1, including:
    a. Analyse speed survey prior to signage amendments
    b. Carry out a speed survey post signage amendments, and compare to previous results
    c. Analyse crash history before and after signage amendments
7. Test recommended treatments by using DTMR-QLS's "A Roundabout Numerical Design Tool" (ARNDT) software

Chapter 2 – Literature Review

2.1 Introduction

This literature review seeks to demonstrate how relevant prevailing information, data, and ideas supports or does not support the specific high-speed roundabout topics presented as problem statements in Chapter 1, Section 1.7, including a review of:

- Approach Reverse Curve Geometry
- Circulating Carriageway Crossfall
- Rate of Rotation
- Side Friction

When reviewing the subsequently mentioned relevant texts, the focus has been on how the above-mentioned topics relate to heavy vehicles in particular.

In Australia, the primary national reference for geometric road design standards is the Austroads Guide to Road Design (AGRD) documents. With some exceptions, each state's transport authority then produces a supplementary document to the AGRD. The supplements either: accept the AGRD standards without modifications, provide additional guidance to the standards, or modify the standards to suit the relevant state's preferences and requirements.

The relevant state authority supplements are as follows:

- Queensland – Queensland Department of Transport and Main Roads - Road Planning and Design Manual (RPDM) – 2nd Edition (DTMR-QLD 2017)
- New South Wales – Roads and Maritime Services Austroads Guide Supplement (RMS-NSW 2016)
- Victoria – VicRoads Supplement to the Austroads Guide to Road Design (VicRoads 2011)
- South Australia – N/A – Refer to AGRD without supplement
- Western Australia – Main Roads Western Australia (MRWA) Supplement to Austroads Guide to Road Design (MRWA 2019a)
- Northern Territory – N/A – Refer to AGRD without supplement
- Australian Capital Territory - N/A – Refer to AGRD without supplement
- Tasmania - N/A – Refer to AGRD without supplement

Additionally, various other texts and sources have been reviewed, including United Kingdom and United States of America road design standards.

2.2 Austroads Guide to Road Design (AGRD)

2.2.1 Approach Reverse Curve Geometry

The primary document for Australian roundabout design standards, Austroads (2015a), refers designers to the main Austroads (2016) Geometric Design document for approach reverse curve geometry requirements, however does not give specific roundabout approach advice, and/or clear details on the unique scenario of using reverse curves as a speed reduction device.

As the approach geometry is influenced largely by the central island size, Figure 11 gives the first indication of when speed reduction treatments are required prior to the entry curve.

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

Figure 11 – Guide for selecting the minimum central island radius for a circular roundabout
Source: Austroads (2015a), Table 4.1

The document then outlines the general roundabout Approach and Entry Geometry requirements, including reverse curve geometry as a form of speed reduction treatment.

As per Austroads (2015a) Section 4.5.2 Approach treatments for high-speed areas, this treatment is usually only required in areas with high desired speeds (greater than or equal to 80 km/h posted speed) on the approach leg. It is important to note that the AGRD suggests that successive reverse curves are just one of many speed reduction treatments that can be used in such scenarios, including rumble strips, dense plantings to give the impression of restriction to the driver, large advance warning signs, and flashing lights etc.

Approach reverse curves are however the most common form of treatment, as is evidenced by the continuing text in Section 4.5.2 – Use of approach reverse curves. This section provides an additional two pages of information relating to approach reverse curves, whereas no further information is provided for the other types of speed reduction treatments.

Section 4.5.2 of Austroads (2015a) outlines the reasons for using reverse curves on approaches, gives examples of where they may and may not be used, and gives some advice as to the reduction in speeds that should be achieved on successive curves.

The text goes on to further state "Speeds generated by the Operating Speed Model will often show that excessive superelevation and/or rates of rotation on one or more curves will result, if strictly using the design criteria in accordance with the Guide to Road Design Part 3", however, it fails to high-light the criticality of this issue, particularly for less stable heay-vehicles, and it fails to provide guidance on how to avoid this situation.

Section 4.5 of this document provides one example of a roundabout in a high speed rural environment, using reverse curves, shown in Figure 5.

The example is particularly devoid of several critical elements, for example:

- Crossfall of the circulating carriageway
- Lengths of straights between the reverse curves
- Location and lengths of super-elevation transitions

The guide does refer designers to Austroads (2016) Geometric Design document for further details of the critical relationships between the above mentioned elements, and it does mention that some treatments "may reduce the stability of heavy vehicles and so consideration should be given to the use of alternative (sic) in these cases". The document does not however give specific examples of alternatives to be used in these cases.

2.2.2 Circulating Carriageway Crossfall

Circulating carriageway requirements are covered by Austroads (2015a) Section 4.6. However, much of the information presented is related to the two-dimensional elements of roundabouts, with respect to different design vehicle requirements, and the size and width of the circulating carriageway required to cater for the swept paths of said vehicles.

Circulating carriageway crossfall requirements are covered by Austroads (2015a) Section 4.10 – Superelevation, Gradient and Drainage.

This section mentions that many roundabouts operate satisfactorily with an adverse crossfall of 2.5 to 3 %, however then mentions that a disadvantage of adverse crossfall is that it results in higher single vehicles crashes for trucks, when compared to superelevated carriageways.

It is mentioned that a safe roundabout can be designed with either adverse crossfall or positive crossfall, if the use of approach entry curvature is provided in accordance with Austroads (2015a) Section 4.5, as this will slow the motorists before the roundabout so that the negative effects of the adverse crossfall and/or superelevation are minimised.

Further truck specific advice is provided in this section under the heading – Roundabout radius, crossfall and heavy vehicle stability. This advice outlines the critical relationship between these elements, and does specifically mention a truck stability factor to consider, that being the advice to avoid rapid changes in crossfall, which can cause instability for high heavy vehicles and their loads. The document however does not provide specific examples of geometry to avoid the situation mentioned.

2.2.3 Rate of Rotation

Rate of rotation is not specifically referenced in the Austroads (2015a) Roundabout document, and again designers are referred to the Austroads (2016) Geometric Design document.

In this document, rate of rotation is covered in Section 7.7.7 Rate of Rotation.

For speeds under 80km/h, maximum rate of rotation is specified as 3.5% per second, and for 80km/h and above, maximum rate of rotation is 2.5% per second.

Further information is provided in Commentary 18 (Austroads 2016), and Figure 12 shows rate of rotation and superelevation development length criteria for various operating speeds.

Operating speed (km/h)	Length (m) of superelevation development from normal crossfall to required superelevation			
	–ve 3% to +ve 3%	–ve 3% to +ve 5%	–ve 3% to +ve 7%	–ve 3% to +ve 10%
40(1)	19	25	32	41
50(1)	24	32	40	52
60(1)	29	38	48	62
70(1)	33	44	56	72
80(2)	53	71	89	116
90(2)	60	80	100	130
100(2)	67	89	111	–
110(2)	73	98	122	–
120(2)	80	107	–	–
130(2)	87	116	–	–

1 Rate of Rotation 3.5 % per second
2 Rate of Rotation 2.5 % per second.

Note: Assumed normal crossfall – 3.0%.

Figure 12 –Rate of rotation criteria
Source: Austroads (2016), Table C18.1

As shown in Figure 12, no differentiation is provided between light and heavy vehicle requirements, and there is no information provided with respect to why the rate of rotation is important, and/or the consequences if exceeded.

2.2.4 Side Friction

Side friction is first mentioned in the Austroads (2015a) Roundabout document in Section 3.2.2, where it is noted that "one study has shown that side friction used by the 85th percentile driver can be as high as 0.48 on smaller to moderate radii curves at roundabouts in higher speed areas".

Aside from the above, side friction is scarcely mentioned in the Austroads (2015a) Roundabout document, and again designers are referred to the Austroads (2016) Geometric Design document.

Figure 7 in Section 1.5 lists the recommended side friction factors for cars and trucks.

2.3 Queensland Department of Transport and Main Roads – Road Planning and Design Manual (RPDM) – 2nd Edition

2.3.1 Approach Reverse Curve Geometry

The DTMR-QLD (2017) supplement accepts all Austroads (2015a) design advice regarding reverse curve approaches, and provides the following additional relevant advice:

- Vertical curves in conjunction with approach horizontal curves are discouraged, and designers are encouraged to consider an alternative treatment to the reverse curves if vertical curves cannot be avoided
- If superelevation is incorporated into the approach curves, short horizontal straights between each curve is recommended
- Superelevation on approach curves is discouraged, and the alternative of using adverse crossfall on one or more of the reverse approach curves is encouraged, to keep the crossfall in the same direction through the approach curves and entry curve

2.3.2 Circulating Carriageway Crossfall

The QLD supplement does not provide any relevant additional advice on the subject of circulating carriageway crossfall.

2.3.3 Rate of Rotation

The QLD supplement does not provide any relevant additional advice on the subject of rate of rotation.

2.3.4 Side Friction

The DTMR-QLD (2017) supplement does not provide any relevant additional advice on the subject of side friction, except to note in Section 4.10.4 that drivers generally use high values of side friction on all geometric elements of a roundabout, and that appropriate consideration should be given to pavement surfacing treatments to cater for this requirement.

2.4 New South Wales – Roads and Maritime Services Austroads Guide Supplement

2.4.1 Design Principles & Approach Reverse Curve Geometry

The RMS-NSW (2016) supplement to Austroads (2015a), at only 4 pages in length, is relatively scarce on additional information for designers of high speed roundabouts.

In contrast to other states guidelines, Section 2.3 – Design Principles, states that in NSW, roundabouts are not recommended where the posted speed limit is greater than 80km/h.

Section 4.5.2 – Approach and Entry Treatments, states that reverse curve approaches are not preferred in NSW.

2.5 Victoria – VicRoads Supplement to the Austroads Guide to Road Design

The VicRoads (2011) supplement to Austroads (2015a) does not provide any supplementary comments to the relevant Austroads standards.

2.6 Western Australia – Main Roads Western Australia (MRWA) Supplement to Austroads Guide to Road Design

In general, the MRWA (2019a) supplement appears to provide the most detailed and comprehensive supplementary information relating to high speed roundabouts, and roundabouts in general, when compared to the other available supplements.

This is immediately evident in the provision of detailed example drawings, under Section 4.1.1 – Design Steps, of the MRWA supplement, describing and providing examples of the initial steps of the geometric design of a roundabout, in accordance with the Austroads (2015a) method. Figure 13 shows an excerpt of the example, and the full-size drawing is attached as Appendix D.

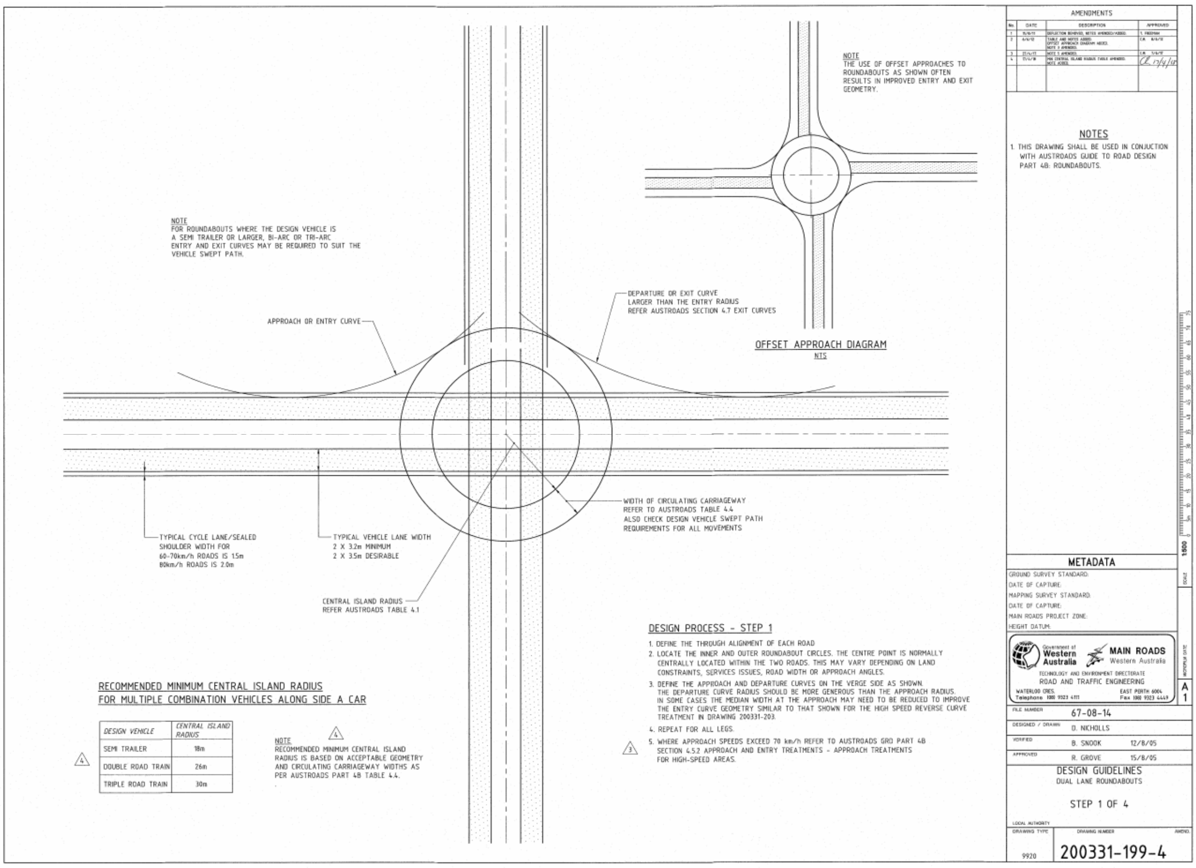


Figure 13 –Roundabout design steps example

Source: MRWA (2019a), Drawing No. 200331-199-4

2.6.1 Approach Reverse Curve Geometry

A particularly useful and interesting additional piece of advice is provided in the MRWA Supplements Section 4.5.2 - Approach and Entry Treatments. In this section it is advised that for rural and high speed roundabouts which have posted approach speeds of 80km/h and higher, it is mandatory to include supplementary geometric devices on the approaches to encourage drivers to slow to an appropriate speed before entering the roundabout. The document states that the MRWA preferred treatment is successive reverse curves, and a detailed example is shown below in Figure 14, with full-size drawing attached as Appendix E.

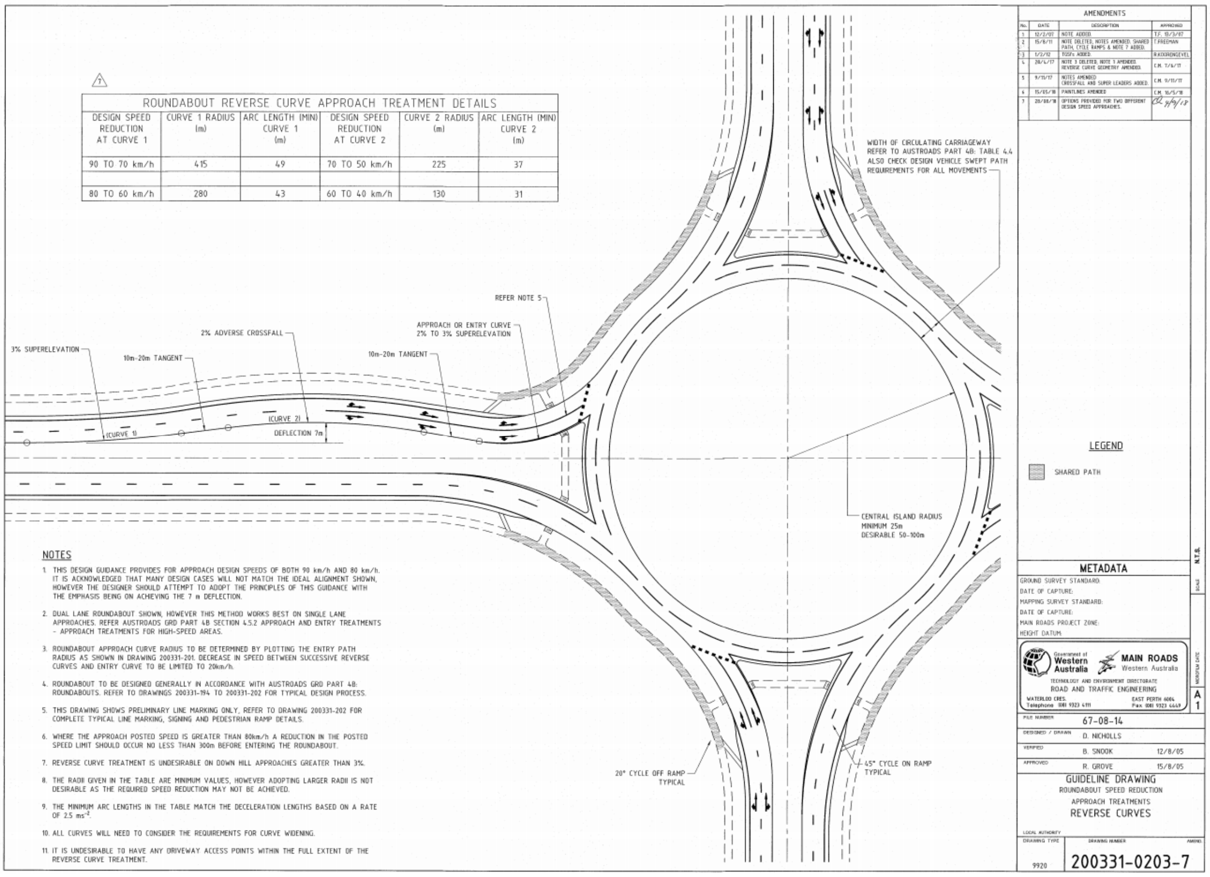


Figure 14 – MRWA Approach Reverse Curve Geometry

Source: MRWA (2019a), Drawing No. 200331-0203-7

Included in the example drawing is the specific curve radii, arc length, and separating tangent lengths required to achieve the desirable approach geometry, for both 90km/h and 80km/h design approach speeds (80km/h and 70km/h posted speeds).

2.6.2 Circulating Carriageway & Approach Curve Crossfall

A specific item that is missing from the drawing is the specification of the circulating carriageway crossfall, ie whether it is to be super-elevated, or adverse crossfall. However, MRWA's preference for adverse crossfall is stated in the subsequent Section 4.10 – Superelevation, Gradient and Drainage, and it is noted that this is to avoid the need for a superelevation rollover at the entry curve.

In this section, there is more emphasis placed on the affects that roundabout geometry has on heavy vehicle stability than any other widely available Australian road design standards.

Figure 15, shown below, is an excerpt from the MRWA document that highlights design features that contribute to destabilisation of high centre of gravity (HCoG) trucks, and a risk reduction methodology for each relevant design feature. This exemplifies the additional guidance provided in the MRWA document.

HCoG Destabilising Design Features	Risk Reduction Methodology
Approach speed	Manage approach speeds in accordance with Main Roads supplement to Austroads GRD Part 4B,section 4.5.2
Approach reverse curves	Ensure the curves are adequate for the operating speed with speed reduction limited to 20 km/h per curve Ensure that the curves are long enough to allow for a comfortable deceleration rate (2.5 ms^{-2}). An important design element in the approach reverse curves is to provide a short tangent between curves, this reduces the dynamic effect caused by truck suspension.
Changes in superelevation direction	Rates of rotation should not exceed the maximums. Also by adding short tangents between curves improves superelevation rotation rates, and superelevation can then be located correctly. Having the circulating carriageway as adverse superelevation avoids the need for a superelevation rollover at the entry curve.
Fold or ridge through the centre of the roundabout	Avoid folds or ridgelines in roundabouts, or if unavoidable then limit the changes in grade to 4% and make the vertical curve joining the grades as long as possible.
Kerbing	Ensure that the correct design vehicles are adopted for tracking and ensure that adequate clearance to kerbing is achieved. Consider mountable Type A kerbing for the central island to reduce destabilising affect produced by semi-mountable kerbing, if mounted by HCoG trucks.

Figure 15 – Example Design Features Affecting HCoG Truck Stability
Source: MRWA (2019a), Table 4.10.1

Further supplementary advice, over and above that of the Austroads and all other states supplements, is the advice for designers to assess truck stability at roundabouts by use of simulation software such as TruckSim, HVE, and UM Truck and Trailer.

The MRWA supplement mandates that all roundabouts meeting the following criteria should be assessed for stability using simulation software:

- Freeway and highway exit ramp approaches to roundabouts where the approach posted speed is 80km/h or greater, especially where the crossing road is under the main alignment. For these assessments the high speed roundabout approach treatment must also be assessed if adopted.

- Rural roundabouts where the approach posted speed is 80km/h or greater. The approach treatment should also be included in the assessment if adopted.
- All roundabout approaches where the posted speed is 70 km/h and no approach treatment has been provided.

Specific vehicle characteristics to be used in the assessment are provided in the supplement, such as payload heights, payload density specifications, and trailer deck heights, and a specific Load Transfer Ratio (LTR) of 0.6 is provided as the maximum value for trucks to not exceed when negotiating a roundabout at 30km/h.

As per the MRWA guidance, the assessment is based on estimating the Load Transfer Ratio (LTR), which is a measure of the proportion of the vehicle's load carried by the tyres on the outside of a curve. An LTR of 1.0 implies that 100% of the load is carried by the outside tyres and the vehicle will tip over.

It is recommended that simulation outputs including LTR values should be plotted against a vehicle path profile, so that designers and reviewers can identify any geometric features that are governing the design.

2.6.3 Main Roads Western Australia – Guidelines for Vehicle Stability Analysis – Main Roads Internal Process

Included in the MRWA (2019a) document is reference to an additional stand-alone document (MRWA 2019b) that provides specific guidance to designers for vehicle stability analysis.

As per Section 1 of the document: *The purpose of this document is to provide guidance on the process to be followed to assess the stability of heavy vehicles on the approach to and through roundabouts as well as on loop ramps and other tight geometric elements.*

The document outlines the process to be undertaken by designers to carry out the assessment, which can be summarised as follows:

1. Create vehicle centreline alignments using AutoTurn or AutoTrack CAD software – example shown in Figure 16
2. Create 3D vehicle alignment and camber strings using 3D model of the roundabout, ie in 12D Civil Design Software
3. Report XYZ points of the vehicle centreline and camber strings and export to Excel spreadsheet – example shown in Figure 17
4. Determine design vehicle – typically the highest risk vehicle permitted to operate on the relevant section of road
5. Carry out the stability analysis using "Universal Mechanism" simulation software

6. Export the results and graph the LTR relative to the vehicle location – example output shown in Figure 18

7. Identify locations where LTR > 0.6

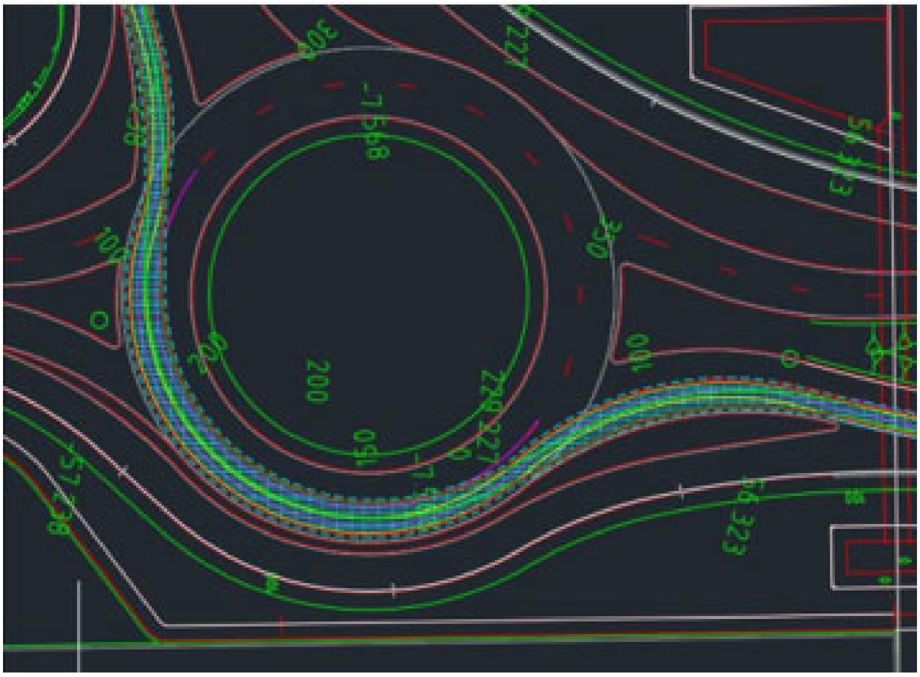


Figure 16 – Centreline path through a roundabout with swept paths

Source: MRWA (2019b), Figure 1

	A	B	C
1	Time (second)	Distance	Vehicle LTR
2	28.12047195	234.6955	0.568903506
3	28.14047241	234.8662	0.573803186
4	28.16047287	235.0372	0.574815273
5	28.18047333	235.2081	0.577029049
6	28.20047188	235.3789	0.583529532
7	28.22047234	235.5496	0.592311323
8	28.24047279	235.7201	0.600963235
9	28.26047325	235.8907	0.609190285
10	28.2804718	236.0612	0.61697185
11	28.30047226	236.2318	0.623608887
12	28.32047272	236.4023	0.62821579
13	28.34047318	236.5728	0.630037844
14	28.36047173	236.7432	0.628466368
15	28.38047218	236.9134	0.623369753
16	28.40047264	237.0834	0.615005374
17	28.4204731	237.2531	0.603779078
18	28.44047356	237.4225	0.590319812

Figure 17 – Sample output from stability analysis software showing LTR

Source: MRWA (2019b), Figure 3

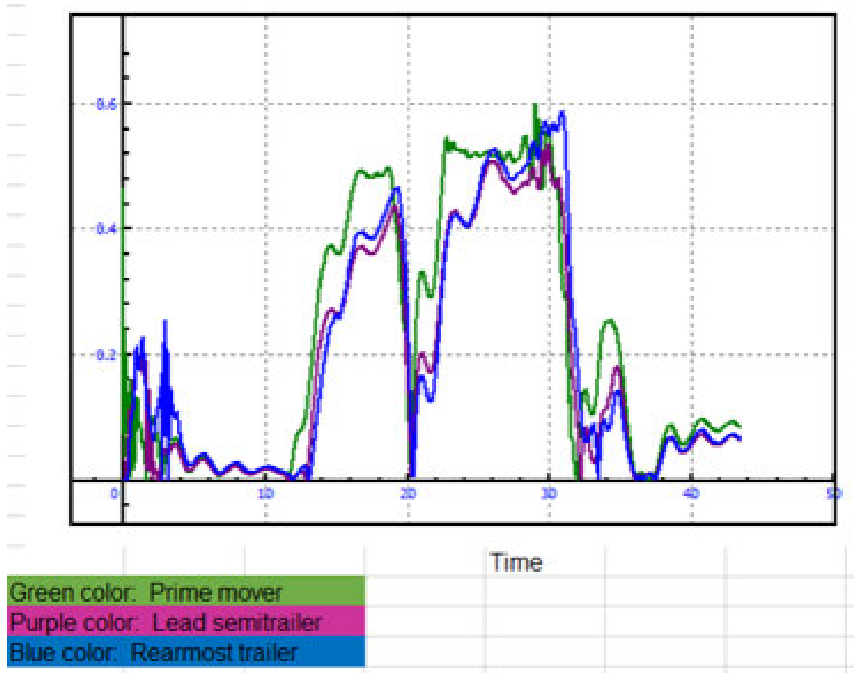


Figure 18 – Graphical output from stability analysis software for various vehicle types
Source: MRWA (2019b), Figure 4

The process guideline concludes by outlining potential mitigation strategies to reduce the risk of vehicle rollover, if required. These range from modifying the intersection geometry to increase vehicle turn path radii, reducing rapid changes in grade, and installing truck rollover warning signs, however it is noted that installing warning signs should be a last resort, with other high hierarchy methods taking preference.

2.7 Florida Department of Transport Design Manual – 213 Modern Roundabouts

2.7.1 Approach Reverse Curve Geometry

The FDOT (2019) standard features reasonably detailed guidance on approach reverse-curve geometry in Section 213.3.1: High-Speed Approach Geometry. Examples for various approach speeds of 50mph (80km/h) and up are provided, shown below in Figure 19:

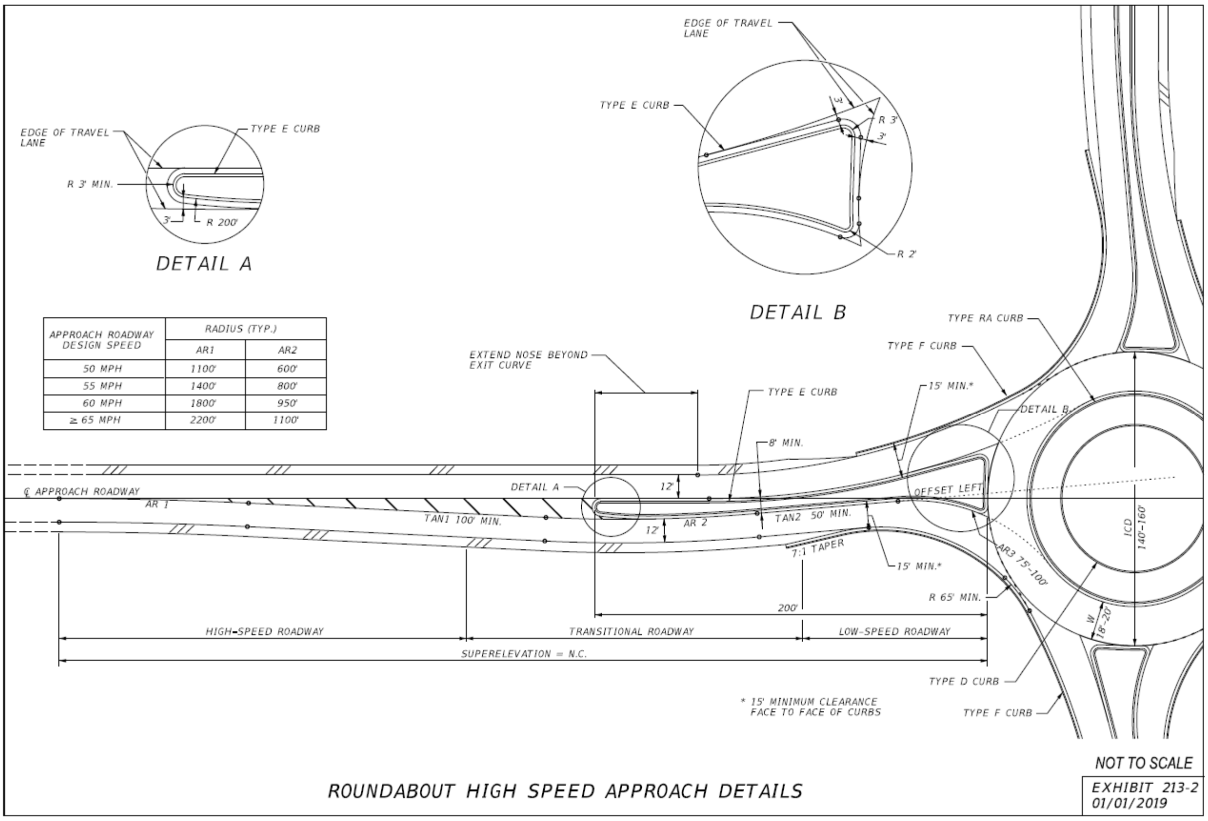


Figure 19 – FDOT roundabout high-speed approach examples
Source: FDOT (2019) Exhibit 213-2

Arc radii and tangent lengths are specified on the example, as are circulating carriageway radii and widths.

2.7.2 Circulating Carriageway Crossfall

The FDOT (2019) standard specifies that the circulating carriageway crossfall slopes away from the central island, ie adverse crossfall, at 2%.

2.7.3 Rate of Rotation

FDOT (2019) Section 213.3.1 specifies that adverse crossfall is used for curves AR2, and the circulating carriageway, therefore no superelevation transitions are required, negating the need for guidance on rates of rotation.

2.7.4 Side Friction

Specific roundabout considerations regarding side friction factors are not provided in the FDOT (2019) standards, and designers are referred to the general AASHTO (2011) standards, which are generally in line with Australian standards.

2.8 United Kingdom – Highways England – Design Manual for Roads and Bridges – CD 116 – Geometric Design of Roundabouts

The UK DMRB (2019) does not provide any relevant guidance for the design of high-speed roundabouts to suit heavy vehicles.

2.9 Critical Roundabout Elements – A holistic review

Through this literature review, and in line with the Problem Statement in Section 1.7, it has become apparent that the following roundabout design elements are critical when it comes to heavy vehicle stability:

- Operating Speed Model & Limiting Curve Speed
- Side friction demand
- Operating speed differential to light vehicles
- Crossfall transitions

With these elements front-of-mind, and in addition to the above documents, various other texts have been reviewed, including international standards and reports, with their findings discussed below.

2.9.1 Operating Speed Model & Speed Prediction

In Australia, according to Austroads (2016), the term "Operating Speed" refers to the 85th percentile speed of cars, ie the speed at or below which 85% of cars are observed to travel under free flowing conditions.

"Desired Speed" is the speed that drivers want to operate at, and is equal to the speed that drivers will adopt on less constrained alignments featuring longer straights and large radius horizontal curves. On high standard roads where speed is expected to be uniform, desired speed will often equal operating speed, and on road where operating speeds are expected to be variable, desired speed will often be higher than operating speed.

"Design Speed" is a fixed speed for the design and correlation of geometric features of a carriageway that influence vehicle operation. The design speed should not be less than the expected operating (85th percentile) speed.

When designing restoration or modification of existing road projects, operating speeds should be measured from speed studies, where possible. Where this is not possible, and/or for design of new roads, the Operating Speeds should be determined using the "Operating Speed Model".

The "Operating Speed Model" is largely determined by the horizontal curves, particularly those less than a radius of 600m. In turn, speed on curves is largely determined by driver behaviour. As per Austroads (2016) section 3.6.1, a typical driver travelling on a long straight followed by a curve, will travel at the desired speed until within approximately 75m of the curve. The driver will then decelerate to a speed that is considered safe for the curve ahead. Car drivers are likely to enter the curve at a speed that is high for the curve, and continue to decelerate within the curve, commonly within the first 80m.

Truck drivers will generally decelerate to what they consider the appropriate speed before the start of the curve, because of the dangers associated with trucks braking on curves.

The "Operating Speed Model" employed by Austroads is for cars only, and Austroads (2016) recommends that truck speeds should be measured where possible. Where it is not possible, truck operating speeds are to be estimated using the Operating Speed Model for cars, and modify for trucks, as per Figure 20:

Car speed (km/h)	40	50	60	70	80	90	100	110
Truck speed (km/h)	34	43	52	60	70	80	90	100

Note: On high speed rural roads and freeways, truck speeds equal car operating speeds.

Figure 20 – Car/Truck Speed Relationship
Source: Austroads (2016), Table 3.5

The DTMR-QLD (2016) supplement, in section 3.6.1, mentions that the DTMR-QLD freely available software package "OSRoad" may be used to assess operating speed. "OSRoad" automates the process described above. The superseded DTMR-QLD (2007) document explains and outlines in detail the uses of the OSRoad software. In this document, it is explained that on relatively small and short horizontal curves, such as those commonly found on roundabouts, vehicles will drive a path that may be substantially larger than the horizontal curve radius. In these cases, it is recommended to use the DTMR-QLD software "ARNDT" (A Roundabout Numerical Design Tool), as this software includes features that calculates vehicle path radii through such curves, as well as operating speed prediction specifically for the smaller, slower and shorter curves found at roundabouts.

2.9.2 Limiting Curve Speed

A critical concept that all above-mentioned speed prediction methods incorporate is the "Limiting Curve Speed" concept. A useful definition of the Limiting Curve Speed is provided in the superseded DTMR-QLD (2007), where it is defined as the speed at which a vehicle travelling on a curve of given radius and superelevation, will have a side friction demand equal to the absolute maximum recommended value for that speed.

Simply put; drivers will adjust their speed (based on their perception of the curve, as mentioned above in section 2.7.1) so that the maximum comfortably tolerable value of side friction is not exceeded.

The question then becomes, what is the maximum comfortably tolerable value of side friction, and does it differ significantly between cars and trucks?

2.9.3 Side Friction Demand & Heavy Vehicle Roll Over Threshold

All roundabouts, even those in lower speed areas without geometric speed reduction elements on the approaches, are essentially a series of relatively short reverse curves, ie drivers negotiate a left-hand curve on the entry, a right-hand curve on the circulating carriageway, and a left-hand curve as they exit the roundabout. The speed at which drivers negotiate these curves is directly related to the Limiting Curve Speed concept described above.

Two critical elements of Australian roundabout design theory are:

1. Maximum entry path radii criteria, which limits the entry speed to a maximum of 60km/h, and
2. The desirable values for central island radii shown in Table 4.1 of Austroads (2015a) which are based on achieving a maximum decrease in speed between the entry curve and a right-turn on the circulating carriageway of 20km/h.

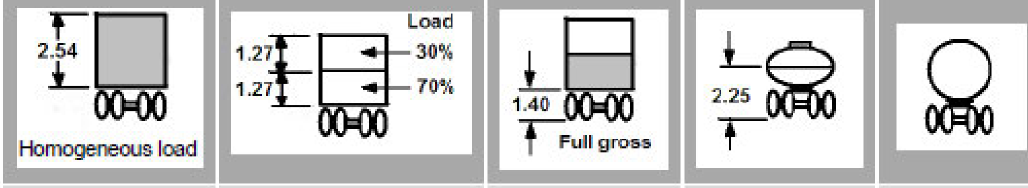
These criteria are based on the work of Dr Owen Arndt, his software program ARNDT (A Roundabout Numerical Design Tool), and his papers Arndt (1998) and Arndt (2001).

Arndt's papers further the work of the United Kingdom's Maycock and Hall (1984), and summarises his own studies of relationships between roundabout geometry and accident rates, which analysed 100 different roundabouts in Australia in the late 1980's and 1990's. Arndt (1998) describes the modification of Maycock and Halls speed estimation model to suit the smaller radii and speeds at roundabouts, which limits the side friction to 0.5, which appeared as a general maximum recorded by Maycock and Hall.

Therefore, the predicted vehicle speeds associated with complying with the Austroads (2015a) "Maximum Entry Path Radius" and central island radius criteria, are based on the assumption that vehicles will negotiate these elements at side friction values as high as 0.5. This is further evidenced in Austroads (2015a) Section 3.2.2, where it is mentioned that "one study has shown that the side friction used by the 85th percentile driver can be as high as 0.48 on smaller to moderate radii curves at roundabouts in higher speed areas".

The issue is that cars can tolerate the above mentioned higher coefficients of side friction, however there is substantial evidence that trucks can become unstable at much lower values of side friction than 0.5. Furthermore, it is known that cars have a larger margin for error regarding side friction than trucks, for example, if a car generates more side friction than it is capable of, it will typically slide, whereas a truck will typically roll, due to their higher centre of gravity.

Several studies, including Ervin et al (1985), as mentioned in Austroads (2017b) have correlated critical heavy vehicle lateral acceleration (also known as rollover threshold) with heavy vehicle coefficients of side friction. For example, if a given vehicles rollover threshold is 0.24g, f = 0.24 can be construed as a friction factor at which the vehicle is likely to overturn. Ervin et al (1985) found that the least stable heavy vehicles will roll at 0.24g / f = 0.24. Various other heavy vehicle load cases and their roll over thresholds are shown below in Figure 21:



Loading					
Rollover Threshold	0.24 g	0.28 g	0.34 g	0.32 g	0.26 g
Centre of gravity height	2.67 m	2.41 m	2.12 m	2.25 m	2.54 m

Figure 21 – Various heavy vehicle load cases and associated rollover thresholds
Source: Ervin et al (1985)

Other studies, such as Mai & Sweatman (1984), found that the least stable heavy vehicles are likely to roll over at friction factors as low as 0.25, with common forms of heavy vehicles, eg tankers and multi-level cattle trucks, featuring rollover thresholds of 0.26 and 0.34 respectively.

2.9.4 Conclusion

The speeds at which heavy vehicles can negotiate a given roundabout element needs to be considerably less than that of light vehicles, and certain provisions need to be made in order to facilitate this requirement:

- Increased curve radii for a given speed
- Increased awareness through signage
- Increased length of straights between curves (to allow for the previously mentioned fact that trucks tend to brake only on the straights, compared to cars which can decelerate into the curves).

In general, even considering the Austroads Guide to Road Design standards alone, it could be argued that all the relevant information is available and referenced accordingly, and that a very competent designer, experienced and proficient in high-speed roundabout design, is able to locate, understand, combine and implement the necessary criteria to achieve a satisfactory high-speed roundabout design.

However, as has been demonstrated by this literature review, and as is evident in the case-studies of RB1 and RB2, there is a large margin for error by having the necessary information spread across multiple sources and documents.

In addition, there are insufficient examples provided for combinations of design elements to suit a given typical arrangement, and there is insufficient emphasis on the criticality of heavy vehicle stability on roundabouts.

These conclusions of the literature review highlight the need for analysis and critical review of the current standards, and for additional guidance to be developed. These actions are documented in the following chapters.

Chapter 3 - Methodology

3.1 Methodology Introduction

As introduced in Section 1.8, the key aims of this dissertation are to analyse and evaluate the commonly available standards for high-speed roundabouts, identify where improvements to the standards may be required, and develop a document that clearly and comprehensively details the design standards and guidelines specifically catering to heavy vehicles on high-speed roundabouts.

To achieve the above, two distinct methodologies have been employed:

1. Analysis and critical review of various current roundabout standards and guidelines to assess their appropriateness for the design of high-speed roundabouts to suit heavy vehicles.
2. Case studies of two separate high-speed roundabouts; one (RB1) with perceived issues with heavy vehicles, and another (RB2) with historic perceived issues with heavy vehicles, that have since been rectified.

Based on the learnings of the above mentioned analyses, alternative geometric design criteria has been developed to suit the heavy vehicles.

3.2 Analysis and critical review of current standards

As identified in the literature review of various state, national, and international road-design standards, heavy vehicle capabilities and associated driver behaviours vary significantly to light vehicles. Roundabout geometric standards however, are typically based on the capabilities and driver behaviours of light vehicles. Therefore, a potentially significant gap exists between the safety performance of a roundabout designed to the current standards, and the capabilities of heavy vehicles.

As such, a critical review of various current roundabout standards has been undertaken.

Critical elements to heavy vehicle roundabout design, as identified in the literature review, have been focused on during this analysis. The following elements, and the methods employed to analyse them, are described below.

3.2.1 Analysis and critical review of current central island radius and circulating carriageway width standards (40 – 70 km/h)

Recommended central island radii and circulating carriageway widths are given in Austroads (2015a) Tables 4.1 and 4.3, presented below as Figure 22 and Figure 23:

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.*

Figure 22 – Guide for selecting the minimum central island radius for a circular roundabout

Source: Austroads (2015a), Table 4.1

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 23 – Initial selection of single lane roundabout circulating carriageway widths

Source: Austroads (2015a), Table 4.3

Together, the values provided dictate the right-turn/circulating carriageway radii.

The central island radii are associated with desired driver speeds on the fastest leg prior to the roundabout, and subtraction of the desirable decrease in speed (20km/h) between the entry curve and a right-turn on the circulating carriageway yields the associated right-turn/circulating carriageway radii.

With the right-turn radii and speeds known, calculation of the required coefficients of side-friction was then carried out for both superelevated and adverse crossfall carriageways, using Equation 10 of Austroads (2016):

$$f_1 = \frac{V^2}{127R} - e_{1\ \mathrm{rounded}}$$

Where:

f = side friction factor

V = speed (km/h)

R = curve radius

e = carriageway crossfall

The resulting coefficients of side friction were then compared to the critical coefficients of side friction related to heavy vehicle roll overs, as found in the literature review.

Only the radii and widths for the 40 – 70km/h scenarios were analysed in this way. For the 80 and 90 km/h scenarios, where speed reduction treatments are recommended prior to the entry curve, an alternative analysis method was employed, described in Section 3.2.3.

3.2.2 Development of recommended central island radii and circulating carriageway widths

Following the above analysis and review, recommended central island radii and circulating carriageway widths were developed for a single lane roundabout to suit a 19m Semi-Trailer.

The following methodology was employed to develop the recommendations:

1. Desired driver speeds on fastest leg prior to the roundabout determined in line with Austroads (2015a).
2. Calculated right-turn/circulating speeds, based on Austroads (2015a) desirable 20km/h decrease between the entry curve and a right-turn for cars, plus an additional 5 – 10km/h decrease for trucks, depending on speed, in line with Austroads (2016) Part 3 Section 3.7 and Table 3.5.
3. Consideration of two different circulating carriageway crossfalls. To reduce issues associated with grading superelevation transitions between the entry curve and the circulating carriageway, it is recommended that adverse crossfall on the circulating carriageway is adopted. This requires

a coefficient of side friction of 2/3 of the absolute maximum recommended, in line with Austroads (2016) Part 3 Section 7.8 and Table 7.12, and Part 4B Appendix B, Section B.3. To provide recommendations for scenarios where space is constrained, superelevated carriageways have also been considered.

4. Determination of appropriate coefficients of side friction for circulating carriageway based on findings from the literature review. General maximum recommended f = 0.3 for superelevated carriageways, f = 0.2 for adverse crossfall carriageways. Ervin et al (1985) found that the least stable heavy vehicles may roll at f = 0.25, where other studies, for example Mai and Sweatman (1984) found that the typical roll over threshold was f = 0.35. Therefore, f = 0.3 was chosen for the superelevated scenario, as it provides suitable capability for most heavy vehicles. Use of the roundabouts by vehicles requiring f lower than 0.3 is assumed to be very low likelihood, and the drivers of these vehicles are assumed to be aware of the risks and limitations associated, and will reduce their speeds further accordingly. For the adverse crossfall scenario, a coefficient of side friction of 2/3 of the absolute maximum is recommended, in line with Austroads (2016) Part 3 Section 7.8 and Table 7.12, and Part 4B Appendix B, Section B.3.
5. With speed, crossfall, and f known, right-turn/circulating radii can be calculated.
6. AutoTURN vehicle tracking software was then used to determine required central island radius, and circulating carriageway width to suit chosen design vehicle, allow 0.5m clearance either side of swept path.

3.2.3 Analysis and critical review of current reverse curve approach geometry

The geometry of various current examples of reverse curve approaches to high speed roundabouts found in the literature review were analysed and critically reviewed:

- Austroads (2015a) Figure 4.4
- MRWA (2019a) Drawing No. 200331-0203-7 – Variant 1 – 90km/h
- FDOT (2019) Exhibit 213-2 – 55mph

The following methodology was employed to compare the examples to the recommended geometry:

1. The specified operating speeds, curve radii, crossfalls, and lengths of tangents between curves was entered into table.
2. The corresponding coefficients of side friction were calculated for each curve, and compared to the absolute maximum values of Austroads (2015a).
3. The intended decrease in speeds between curves was calculated, and compared to the desirable maximum decrease of 20km/h as per Austroads (2015a)

4. Deceleration lengths required between curves were calculated, and compared to the length of tangents specified in the examples
5. Average speeds between curves were calculated, and used to calculate recommended 0.7V tangent lengths, which were then compared to the length of tangents specified in the examples

3.2.4 Development of recommended reverse curve approach geometry

Recommended reverse curve approach geometry for a single lane roundabout to suit a 19m Semi-Trailer in an 80km/h posted speed environment was developed using the following methodology:

1. Decreasing operating speeds for the successive curves were calculated based on Austroads (2015a) maximum desirable 20km/h decrease in speed between successive elements
2. Recommended curve crossfalls were determined based on findings from the literature review. Curve 2 and the circulating carriageway are recommended to be adverse crossfall to avoid the issues associated with superelevation transitions.
3. Recommended coefficients of side friction were determined based on the findings of the literature review. For example, f = 0.3 has been chosen for a superelevated scenario, as it will provide suitable capability for most heavy vehicles. Use of the roundabouts by vehicles requiring f lower than 0.3 is assumed to be very low likelihood, and the drivers of these vehicles are assumed to be aware of the risks and limitations associated, and will reduce their speeds further accordingly. For the adverse crossfall scenario, a coefficient of side friction of 2/3 of the absolute maximum is recommended, in line with Austroads (2016) Part 3 Section 7.8 and Table 7.12, and Part 4B Appendix B, Section B.3.
4. Curve radii were then calculated based on the above-mentioned speeds, crossfalls, and side friction factors. These curve radii are the actual travelled path of the heavy vehicles.
5. The required deceleration distances between curves was calculated, based on the previously mentioned operating speeds, using a deceleration equation.
   - The deceleration equation has been derived by modification of the Stopping Sight Distance (SSD) Equation 1 of Austroads (2016): $\text{SSD} = \frac{R_T V}{3.6} + \frac{V^2}{254(d + 0.01a)}$
   - The modification to the equation involves the removal of the Reaction Time (R_T) component, and rearranging the remainder of the equation to subtract the total deceleration length of Speed 2 (V2) from the total deceleration length of Speed 1 (V1), which gives the resultant deceleration length.
   - The modified equation is: $D = \frac{V1^2}{254(d+0.01a)} - \frac{V2^2}{254(d+0.01a)}$

- Where:
  - D = Deceleration Length (m)
  - V1 = Speed 1 / Speed at start of straight
  - V2 = Speed 2 / Speed at end of straight
  - d = deceleration coefficient (0.29)
  - a = longitudinal grade (ignored for simplicity and due to typical flat grades at roundabout approaches)

6. The average speeds between successive curves were calculated, and then lengths of straights required were calculated based on the 0.7V criteria, which was found to be critical in the literature review.
7. The longer of the lengths from Steps 5 and 6 were used as the recommended lengths of straights required between successive curves.
8. The geometry was then constructed in AutoCAD
9. AutoTURN vehicle tracking software was then used to determine required central island radius, and circulating carriageway width to suit chosen design vehicle, allowing 0.5m clearance either side of swept path.

The recommended approach geometry was then assessed using ARNDT software, using the following process:

1. ARNDT model developed for the RB1 roundabout, using the original as-constructed geometry, the intended operating speeds, and the measured traffic flow parameters as inputs
2. Report generated in ARNDT giving predicted speeds, accident types and rates
3. The original model's geometry was then modified using the recommended approach geometry; all other parameters left as per original
4. Report generated in ARNDT giving predicted speeds, accident types and rates
5. The original vs modified reports were then compared, to determine which version provided the most appropriate geometry

3.2.5 Signage review and recommendations

It was found in the literature review that the theory of reverse curve approaches acting as speed reduction devices relies heavily on drivers:

- Visually assessing the curve, and determining what speed is considered safe for the curve ahead
- Decelerating to the appropriate speed for the curve by the start of the curve (unlike car drivers going into the curve)

The limiting curve speed for a given radius can vary significantly dependent upon the superelevation or adverse crossfall of the curve, and etermination of the crossfall can be difficult to assess visually from the driver's seat.

In the literature review, state and national standards were reviewed to determine what signage is currently recommended at high speed roundabouts. It was found that the MUTCD (2018) and TMR (2019) provided the most guidance for roundabout signage, and/or the widest range of potential other signs that could be used to assist heavy vehicle driver's decision process at high-speed roundabout approaches.

To develop recommended treatments, the MUTCD (2018) and DTMR-QLD (2019) documents were reviewed to determine what other signage may be available and/or appropriate to assist heavy vehicle drivers decision process at high-speed roundabout approaches. Empirical recommendations were then made based on the advice given in the relevant standards with regards to the warrants for deciding to use or not use a given sign in a given scenario.

3.3 Case Study – Roundabout 1 (RB1)

3.3.1 Methodology Introduction

As introduced in Section 1.7.6, a case study was assessed for a roundabout (RB1) with perceived issues with heavy vehicle usage, in an effort to determine if the geometric features of the roundabout were contributing to the perceived issue. To assess the roundabout, it was determined that an analysis of heavy vehicle stability was required.

Ideally, this would be carried out in accordance with MRWA (2019a) standards, ie their recommended "Load Transfer Ratio" (LTR) analysis. The LTR method requires complex computer simulation with specialised software. This was investigated and considered, however, it was found that this capability is limited in Australia to only a few specialised companies, at a cost that is outside the scope and limitations of this project (typically $5000 - $10,000).

Therefore, an alternative method for analysing vehicle stability was considered. During the literature review, it was found that several studies, including Ervin et al (1984), as mentioned in AGRD (Part 3), had correlated critical heavy vehicle lateral acceleration (also known as rollover threshold) with heavy vehicle coefficients of side friction. For example, if a given vehicles rollover threshold is 0.24g, f = 0.24 can be construed as a friction factor at which the vehicle is likely to overturn.

Other studies, such as Mai & Sweatman (1984), found that the least stable heavy vehicles are likely to roll over at friction factors as low as 0.25, with common forms of heavy vehicles, such as tankers and multi-level cattle trucks, featuring rollover thresholds of 0.26 and 0.34 respectively.

Noting the limitations in obtaining and using the LTR software, the method adopted in this dissertation to analyse the heavy vehicle stability was to calculate the actual coefficients of side friction being relied upon by heavy vehicles negotiating RB1, and identify if any values above the typical roll over thresholds were being generated.

To allow for this analysis, the following information was required:

- Crash History Review
- Speed Survey and Analysis
- Travelled path analysis – both horizontally for determination of travelled path geometry, including lengths of straights and radii of curves, and vertically for determination of crossfalls

Further detail on the purpose and source of the above information is provided below.

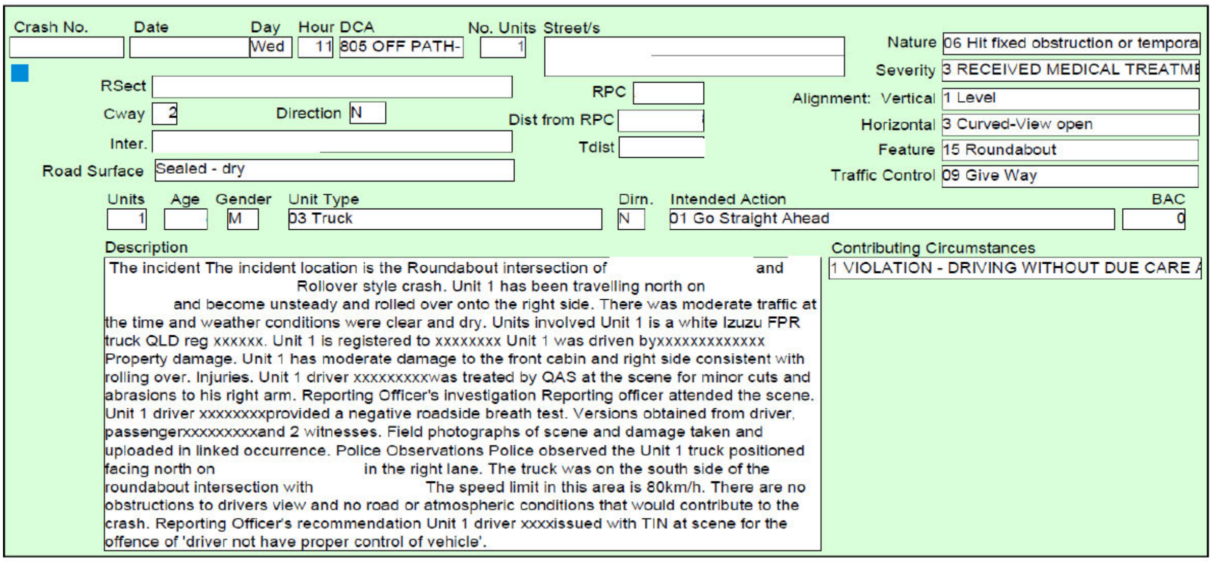
Collection of the above data also enabled other geometric analyses to be carried out, including crossfall rate of rotation, and vehicle deceleration, which were found in the literature review to be important elements affecting heavy vehicle stability at roundabouts.

3.3.2 Crash History Review

A review of the available crash history was undertaken, in an effort to determine how, where and why the crashes are occurring. Roundabouts RB1 and RB2 have been in place for less than 10 years, and as previously mentioned, the crashes have occurred over a 5 year period. Therefore, 10 year crash history records were obtained.

The crash history typically consists of reports provided by attending law enforcement officials, via the road authority, and also includes relevant news articles and details from online media outlets.

An example Crash History Report is shown below in Figure 24:



Crash No. | Date | Day: Wed | Hour: 11 | DCA: 805 OFF PATH- | No. Units: 1 | Street/s

Nature: 06 Hit fixed obstruction or tempora

Severity: 3 RECEIVED MEDICAL TREATME

RSect | RPC

Cway: 2 | Direction: N | Dist from RPC

Alignment: Vertical: 1 Level

Horizontal: 3 Curved-View open

Inter. | Tdist

Feature: 15 Roundabout

Road Surface: Sealed - dry

Traffic Control: 09 Give Way

Units	Age	Gender	Unit Type	Dirn.	Intended Action	BAC
1		M	03 Truck	N	01 Go Straight Ahead	0

Description

The incident The incident location is the Roundabout intersection of and Rollover style crash. Unit 1 has been travelling north on and become unsteady and rolled over onto the right side. There was moderate traffic at the time and weather conditions were clear and dry. Units involved Unit 1 is a white Izuzu FPR truck QLD reg xxxxxx. Unit 1 is registered to xxxxxxxx Unit 1 was driven byxxxxxxxxxxxxx Property damage. Unit 1 has moderate damage to the front cabin and right side consistent with rolling over. Injuries. Unit 1 driver xxxxxxxxxwas treated by QAS at the scene for minor cuts and abrasions to his right arm. Reporting Officer's investigation Reporting officer attended the scene. Unit 1 driver xxxxxxxxprovided a negative roadside breath test. Versions obtained from driver, passengerxxxxxxxxxand 2 witnesses. Field photographs of scene and damage taken and uploaded in linked occurrence. Police Observations Police observed the Unit 1 truck positioned facing north on in the right lane. The truck was on the south side of the roundabout intersection with The speed limit in this area is 80km/h. There are no obstructions to drivers view and no road or atmospheric conditions that would contribute to the crash. Reporting Officer's recommendation Unit 1 driver xxxxissued with TIN at scene for the offence of 'driver not have proper control of vehicle'.

Contributing Circumstances

1 VIOLATION - DRIVING WITHOUT DUE CARE A

Figure 24 – Crash History Report Example

Source: Road Authority

The crash history summaries are shown below in Table 1 and Table 2:

Table 1 – RB1 Crash History Summary

RB1 - Crash History Summary							
Date	**Travel Direction**	**Entering/ Exiting**	**Side Rolled onto**	**Location Relative to Roundabout**	**Severity**	**Violation**	**Notes**
Aug 2016	South	Entering	Left	Entering on northern side	Unknown	Unknown	All details derived from media report
Sep 2018	North	Entering	Right	Facing north on the southern side	Received Medical Treatment	Driving without due care and attention	
Sep 2018	South	Exiting	Left	Exiting the roundabout	Received Medical Treatment	Driving without due care and attention	

Table 2 – RB2 Crash History Summary

RB2 - Crash History Summary							
Date	**Travel Direction**	**Entering/ Exiting**	**Side Rolled onto**	**Location Relative to Roundabout**	**Severity**	**Violation**	**Notes**
Apr 2015	North	Exiting	Right (assumed)	Exiting on northern side	Admitted to hospital	-	B-Double - Crash report mentions "load shift"
Aug 2015	South	Entering	Right	Entering on northern side	Received Medical Treatment	-	

3.3.3 Speed Survey

The speed environment at RB1 is posted 80km/h speed limit.

A speed survey and analysis at RB1 was carried out in 2018 by the road authority, via the MetroCount tube method, and speeds and vehicle types were measured over the duration of 7 days at four locations, on the northern and southern approach curves 1 and 3. Refer Figure 25 below.

At these locations, 85th percentile speeds were calculated, and the data was split into 3 vehicle groups:

1. All vehicles – ie Austroads Vehicle Classes 1 – 12
2. Medium and Heavy Vehicles only – ie Austroads Vehicle Classes 3 – 12
3. B-Doubles and Road Trains only – ie Austroads Vehicle Classes 10 – 12

Refer Section 1.6 for Austroads Vehicle Classification details.

Due to the relatively large distances between the data collection points, and the lack of data on the second approach curves, circulating carriageways and exit curves, preliminary investigations as part of this project revealed that additional speed survey data was required at the locations mentioned above, in an effort to reduce the amount of linear interpolation required between the initial data points, and allow for increased accuracy for future vehicle performance calculations.

Therefore, an additional speed survey was carried out in 2019, with data points being collected at six extra locations. Figure 25 below shows the original 2018 locations (1 – 4) and the 2019 locations (A – F)

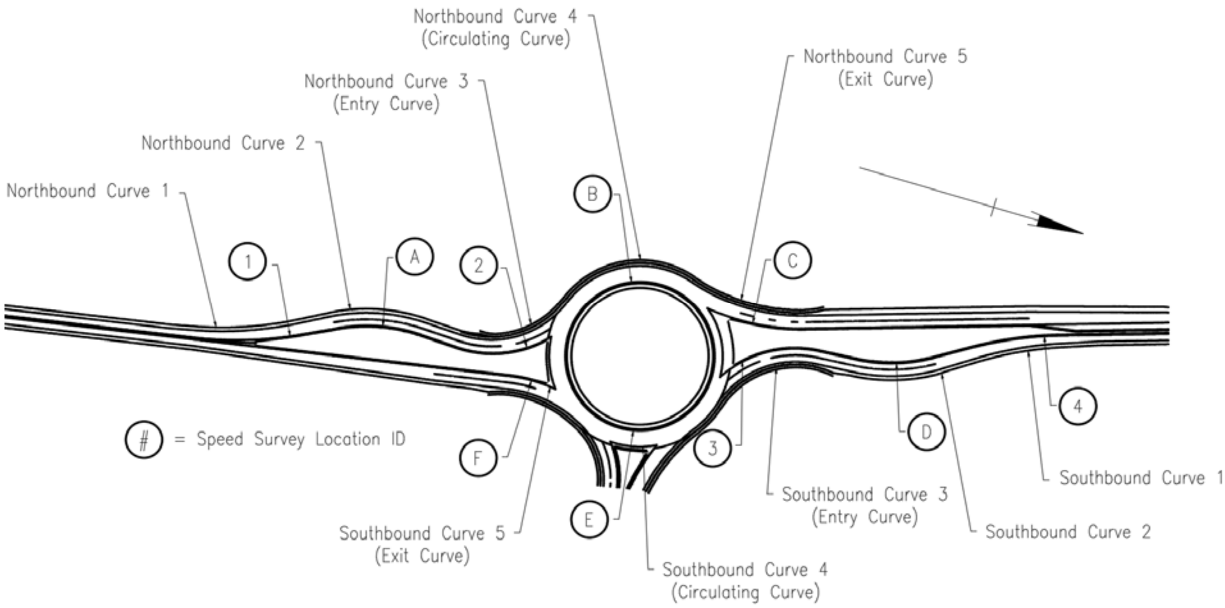


Figure 25 – RB1 – 2017 & 2019 Speed Survey Sites

The 2019 speed survey was carried out via two methods:

1. MetroCount tube method – generally in accordance with the 2017 speed survey – Example output provided below in Figure 26
2. Radar sensor method by Matrix Traffic and Transport Data - – Example output provided below in Figure 27

The 2019 MetroCount data differed to the 2018 data in that the 2019 survey split the data into the following groups, which did not include B-Doubles and Road Trains only, like the 2018 data did:

1. All vehicles – ie Austroads Vehicle Classes 1 – 12
2. Medium and Heavy Vehicles only – ie Austroads Vehicle Classes 3 – 12
3. Heavy Vehicles only – ie Austroads Vehicle Classes 6 – 12

The radar method varied compared to the MetroCount methods in the following ways:

- Radar survey conducted over 3 days, compared to 7 days for the MetroCount surveys
- Radar data split into only two vehicle groups:
  - All vehicles – ie Austroads Vehicle Classes 1 – 12
  - Articulated Heavy Vehicles only – ie Austroads Vehicles Classes 6 – 12

Speed Histogram

B **Northbound on Roundabout**

Datasets:
Site: _B **Northbound on roundabout <80>**
Direction: 1 - North bound, A trigger first. **Lane:** 0
Survey Duration:
Zone:
File:
Identifier:
Algorithm: Factory default axle (v5.02)
Data type: Axle sensors - Paired (Class/Speed/Count)

Profile:
Filter time:
Included classes: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Speed range: 10 - 160 km/h.
Direction: North, East, South, West (bound), P = North, Lane = 0-16
Separation: Headway > 0 sec, Span 0 - 100 metre
Name: speed all vehicles 80kmh Posted
Scheme: Vehicle classification (AustRoads94)
Units: Metric (metre, kilometre, m/s, km/h, kg, tonne)
In profile: Vehicles = 49326 / 49679 (99.29%)

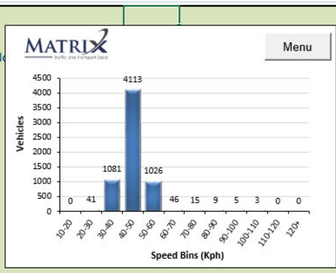
Speed Statistics

Direction: NS
Vehicles = 49326
Posted speed limit = 80 km/h, Exceeding = 3146 (6.378%), Mean Exceeding = 91.56 km/h
Maximum = 145.0 km/h, **Minimum** = 12.6 km/h, **Mean** = 49.6 km/h
85% Speed = 55.71 km/h, **95% Speed** = 83.61 km/h, **Median** = 46.17 km/h
15 km/h Pace = 38 - 53, **Number in Pace** = 35444 (71.86%)
Variance = 192.55, **Standard Deviation** = 13.88 km/h

Figure 26 – RB1 – MetroCount Speed Survey Data Example

Source: Road Authority

Job No	
Client	
Site	A1 Southern entry to Roundabout (travelling N
Location	
Site No	A1
Start Date	
Day	Wednesday
Direction	NB
Description	Speed Summary
Select Site	A1. A1 Southern entry to Roundabout (travelling Northbound)
Select Day	Wednesday
Select Direction	NB



Bin Summary	
10-20	0.0%
20-30	0.6%
30-40	17.1%
40-50	64.9%
50-60	16.2%
60-70	0.7%
70-80	0.2%
80-90	0.1%
90-100	0.1%
100-110	0.0%
110-120	0.0%
120+	0.0%
Over PSL	0.3%

Hour	Vehicle Speed Bins (kph)												Speed						PSL : 80 Km/h
Starting	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120+	Average	Minimum	Median	85th Percentiles	95th Percentiles	Maximum	Over PSL
0:00	0	6	12	9	7	0	0	0	0	0	0	0	55.4	47.0	54.0	62.2	67.2	69.0	0
1:00	0	0	6	9	1	0	0	0	0	0	0	0	55.6	39.0	56.5	64.1	67.4	74.0	0
2:00	0	0	6	20	6	0	1	0	0	0	0	0	61.7	34.0	63.0	70.6	74.6	76.0	0
3:00	0	0	7	20	8	0	0	1	0	0	0	0	58.3	40.0	58.0	66.0	70.0	85.0	1
4:00	0	1	22	41	16	1	1	1	0	0	0	0	59.6	35.0	60.0	68.0	72.0	88.0	1
5:00	0	0	48	226	60	0	2	0	1	0	0	0	61.2	33.0	61.0	70.0	76.0	91.0	1
6:00	0	3	66	269	74	5	0	1	0	0	0	0	57.7	21.0	58.0	67.0	72.0	84.0	1
7:00	0	2	69	376	105	3	1	0	0	2	0	0	58.7	24.0	59.0	67.0	74.0	108.0	2
8:00	0	3	85	361	69	2	2	0	2	0	0	0	58.3	25.0	59.0	67.0	72.6	90.0	2
9:00	0	0	95	258	47	2	0	1	0	0	0	0	54.8	24.0	56.0	64.0	68.0	88.0	2
10:00	0	3	61	266	40	0	2	1	0	0	0	0	56.8	17.0	57.0	66.0	72.5	85.0	1
11:00	0	3	94	239	30	0	0	0	1	0	0	0	58.7	29.0	59.0	68.0	74.2	95.0	2
12:00	0	5	61	222	43	4	1	1	0	0	0	0	58.7	33.0	59.0	67.0	72.0	88.0	1
13:00	0	3	82	236	43	6	1	0	1	0	0	0	59.3	30.0	59.0	69.0	75.0	90.0	1
14:00	0	5	92	226	53	5	1	1	0	0	0	0	59.5	24.0	60.0	68.0	73.0	82.0	1
15:00	0	0	65	352	111	3	1	0	0	1	0	0	59.6	12.0	61.0	69.0	74.0	103.0	1
16:00	0	4	74	415	132	7	1	1	0	0	0	0	60.3	35.0	60.0	68.0	74.0	85.0	1
17:00	0	4	53	230	71	7	0	0	0	0	0	0	57.2	34.0	57.0	65.0	69.0	78.0	0
18:00	0	0	24	157	53	1	0	0	0	0	0	0	58.8	38.0	60.0	67.0	70.0	75.0	0
19:00	0	0	22	55	21	2	0	0	0	0	0	0	55.6	30.0	57.0	63.0	66.0	69.0	0
20:00	0	0	11	54	13	0	0	0	0	0	0	0	52.5	37.0	52.5	62.0	66.0	68.0	0

Figure 27 – RB1 – Matrix Radar Speed Survey Data Example

Source: Road Authority

Given the different methods employed for the speed surveys, which were out of the control of this dissertation, a comparison of the data, and correlation and interpolation was required to determine the most likely 85th percentile speeds at each site. A further complication was that in the 2019 MetroCount survey, the tube count hardware failed at Site A, and no data was recorded there.

A summary of all recorded 85th percentile speeds (both 2018 and 2019) recorded is shown below in Table 3:

Table 3 – All measured 85th percentile speeds

All measured 85th percentile speeds (km/h)										
Speed Survey Type	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
MetroCount All Classes (1 - 12)	78.12		55.08	55.71	63.72	74.97	61.92	52.47	45.9	59.67
MetroCount Med & HV (3 - 12)	74.25		49.41	84.42	63.81	73	58.59	51	45.27	57.42
MetroCount HV (6 - 12)				48.04	58.32		54.54		42.3	51.12
MetroCount BD/RT (10 - 12)	69.21		45.43			68.58		44.46		
Matrix All Classes (1 - 12)		66.7		50.9	63.9		67.5		48.5	61.7
Matrix HV (6 - 12)		50.7		44.6	56.3		54.8		41.8	50.8

Note: The value of 84.42 km/h at Site B for the Medium and HV (3 – 12) category can be considered an outlier and has not been included in further speed analysis calculations. At Site B, the curve radius is 40m, and in line with Operating Speed Model and Limiting Curve Speed criteria as per Austroads (2016), it is physically impossible for a heavy vehicle to carry this speed through such a geometric element, even if a vehicle cutting across lanes, ie driving a radius larger than 40m, was considered. It is assumed that this value is due to a hardware and/or software malfunction at this site.

The four categories initially considered for vehicle performance analysis in this case study are as follows:

1. All Vehicles (Classes 1 – 12)
2. Medium and Heavy Vehicles (Classes 3 – 12)
3. Articulated Heavy Vehicles (Classes 6 – 12)
4. B-Doubles and Road-Trains (Classes 10 – 12)

As shown in Table 1, the only category to have speeds measured at all sites is All Vehicles (1 – 12). Therefore, in lieu of additional speed surveys, speeds were interpolated for the missing sites for the relevant categories, by comparison and correlation of known speed differentials between All Vehicles and the relevant categories, where a speed was measured for both categories at a given site. This process is described below.

Firstly, average All Vehicles speeds were determined by comparing the MetroCount data to the Matrix Data. This was deemed necessary due to the inherent variations in the data collection process of each method, and in an attempt to reduce the margin for error associated with each method.

For example; the MetroCount tube method relies on vehicles driving over pneumatic tube sensors laid across the traffic lanes. The tube sensors measure the number and spacing of axles to determine the vehicle type, and calculates the speeds by measuring how long each axle takes to cross the sensor. On small radius curves such as roundabout approaches, there is a reasonable margin for error due to the angles that vehicles cross the sensors, which can throw out the algorithm used to calculate the speeds and vehicle types.

The radar method, as the name implies, relies on radar technology to "bounce" a signal off the vehicles, measuring their lengths and determining their speeds. Again due to the angles involved at the roundabout approach, and high traffic volumes, a reasonable margin for error exists using the radar method. For example, if there are two vehicles travelling through the radar sensor together, the radar will not count this, as it cannot classify the vehicle type.

Table 4 below summaries the calculations performed to determine the average and interpolated All Vehicles speeds:

Table 4 – Comparison of MetroCount speeds versus Matrix Radar speeds for All Vehicles Classes

Comparison of MetroCount speeds vs Matrix speeds for All Classes (1 - 12) (85th percentile - km/h) and Interpolation										
Speed Survey Type	**Speed Survey Site**									
	1	**A**	**2**	**B**	**C**	**4**	**D**	**3**	**E**	**F**
MetroCount All Classes (1 - 12)	78.12		55.08	55.71	63.72	74.97	61.92	52.47	45.90	59.67
Matrix All Classes (1 - 12)		66.70		50.90	63.90		67.50		48.50	61.70
Difference				-4.81	0.18		5.58		2.60	2.03
Average Difference	1.12									
Average All Classes (1 - 12)	79.24	65.58	56.20	53.31	63.81	76.09	64.71	53.59	47.20	60.69

As shown in the table above, the radar method speeds are generally higher than the tube count method, however reasonable correlation is achieved (within 10% at any given site) and on average, the radar method has measured speeds 1.12 km/h higher than the tube count method. At sites where speeds were measured by both methods, the average speed at that particular site was calculated using the average of the two speeds. At sites where the speed was measured by only one method, the average All Vehicles speeds were then interpolated by adding or subtracting the average difference to the original measured speed, depending on which measurement method had been used for the sites where speeds were only recorded by a single measurement method.

The same method was then used to determine the average Articulated Heavy Vehicle (6 – 12) speeds, as this was the only other category to have speeds measured by both methods.

Table 5 below summaries the calculations performed to determine the average Articulated Heavy Vehicle speeds:

Table 5 – MetroCount speeds vs Matrix Radar speeds for Articulated Heavy Vehicles

Comparison of MetroCount speeds vs Matrix speeds for HV (6 - 12) (km/h)										
Speed Survey Type	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
MetroCount HV (6 - 12)				48.04	58.32		54.54		42.3	51.12
Matrix HV (6 - 12)		50.70		44.60	56.30		54.80		41.80	50.80
Difference				-3.44	-2.02		0.26		-0.50	-0.32
Average Difference	-1.20									
Average HV (6 - 12)		51.90		46.32	57.31		54.67		42.05	50.96

In order to determine the Articulated Heavy Vehicle speeds at the sites where no Articulated Heavy Vehicle speeds had been measured, interpolation was employed, by comparing the average Articulated Heavy Vehicle speeds to the average All Vehicles speeds, at sites where both vehicle categories had speeds measured, and subtracting the average difference from the average All Classes speeds.

Table 6 below summaries the calculations performed to determine the interpolated Articulated Heavy Vehicle speeds:

Table 6 – Comparison of average speeds for Articulated Heavy Vehicles vs All Vehicles

Comparison of average HV speeds (6 - 12) vs average All Classes speeds (1 - 12) (km/h) and Interpolation										
Speed Survey Type	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
Average All Classes (1 - 12)	79.24	65.58	56.20	53.31	63.81	76.09	64.71	53.59	47.20	60.69
Average HV (6 - 12)		51.90		46.32	57.31		54.67		42.05	50.96
Difference		-13.68		-6.99	-6.50		-10.04		-5.15	-9.73
Average Difference	-8.68									
Interpolated HV	70.56		47.52			67.41		44.91		
Combined measured and interpolated HV	70.56	51.90	47.52	46.32	57.31	67.41	54.67	44.91	42.05	50.96

As previously mentioned, B-Double and Road-Train speeds were only measured at some sites, and only via the MetroCount tube method. Therefore, the interpolation process differed slightly compared to the other vehicle categories.

Firstly, comparison of the B-Double and Road-Train speeds to the All Vehicles speeds was carried out, where both categories speeds had been measured at a given site, and the average speed difference determined. Then, the average speed difference was subtracted from the average All Vehicles speeds.

Table 7 below summaries the calculations performed to determine the average and interpolated B-Double and Road Train speeds:

Table 7 – Comparison of B-Double and Road-Train speeds vs All Vehicles

Comparison of MetroCount BD-RT speeds (10 - 12) vs All Classes speeds (1 - 12) (km/h) and Interpolation										
Speed Survey Type	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
MetroCount All Classes (1 - 12)	78.12		55.08			74.97		52.47		
MetroCount BD/RT (10 - 12)	69.21		45.43			68.58		44.46		
Difference	-8.91		-9.65			-6.39		-8.01		
Average Difference	-8.240									
Average All Classes (1 - 12)	79.236	65.584	56.196	53.305	63.81	76.086	64.71	53.586	47.2	60.685
Interpolated BD-RT (10 - 12)	70.996	57.344	47.956	45.065	55.57	67.846	56.47	45.346	38.96	52.445

Similar to the B-Double and Road-Train category, the Medium and Heavy Vehicle (3 – 12) category speeds were only measured at some sites, and only via the MetroCount tube method. Therefore, the same process as the B-Double and Road-Train method above was carried out to determine the average and interpolated Medium and Heavy Vehicle speeds, which is summarised below in Table 8:

Table 8 – Comparison of Medium and Heavy Vehicle speeds vs All Vehicles

Comparison of MetroCount Med & HV speeds (3 - 12) vs All Classes speeds (1 - 12) (km/h) and Interpolation										
Speed Survey Type	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
MetroCount All Classes (1 - 12)	78.12		55.08		63.72	74.97	61.92	52.47	45.90	59.67
MetroCount Med & HV (3 - 12)	74.25		49.41		63.81	73.00	58.59	51.00	45.27	57.42
Difference	-3.87		-5.67		0.09	-1.97	-3.33	-1.47	-0.63	-2.25
Average Difference	-2.39									
Average All Classes (1 - 12)	79.24	65.58	56.20	53.31	63.81	76.09	64.71	53.59	47.20	60.69
Interpolated Med & HV (3 - 12)	76.85	63.20	53.81	50.92	61.42	73.70	62.32	51.20	44.81	58.30

Table 9 below summarises all resulting average and interpolated speeds by vehicle category and site:

Table 9 – Initial summary of average and interpolated 85th percentile speeds

Summary of average and interpolated 85th percentile speeds (km/h)										
Vehicle Category	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
Average All Classes (1 - 12)	79.24	65.58	56.20	53.31	63.81	76.09	64.71	53.59	47.20	60.69
Interpolated Med & HV (3 - 12)	76.85	63.20	53.81	50.92	61.42	73.70	62.32	51.20	44.81	58.30
Combined average and interpolated HV (6 - 12)	70.56	51.90	47.52	46.32	57.31	67.41	54.67	44.91	42.05	50.96
Interpolated BD-RT (10 - 12)	71.00	57.34	47.96	45.07	55.57	67.85	56.47	45.35	38.96	52.45

Interestingly, with a few exceptions, it can be seen that the B-Double & Road-Train (10 -12) category has typically recorded slightly higher speeds than the Articulated Heavy Vehicle (6 – 12) category. This makes little sense given that the B-Double & Road-Train category should feature a higher proportion of the longer and heavier vehicles than the Articulated Heavy Vehicle category. However, given that the B-Double & Road-Train category was only measured via one method (MetroCount tube method) and only at four sites, compared to the Articulated Heavy Vehicle category which was measured via two methods, and at six sites, the Articulated Heavy Vehicle data can be considered more accurate. This, combined with the fact that the Articulated Heavy Vehicle category includes the B-Double & Road-Train vehicles in any case, justifies the decision to disregard the B-Double & Road-Train only data, and use the Articulated Heavy Vehicle category data in lieu.

Table 10 below summarises the vehicle categories and speeds used in the analysis for this case study:

Table 10 – Final summary of average and interpolated 85th percentile speeds

Summary of average and interpolated 85th percentile speeds (km/h)										
Vehicle Category	Speed Survey Site									
	1	A	2	B	C	4	D	3	E	F
Average All Classes (1 - 12)	79.24	65.58	56.20	53.31	63.81	76.09	64.71	53.59	47.20	60.69
Interpolated Med & HV (3 - 12)	76.85	63.20	53.81	50.92	61.42	73.70	62.32	51.20	44.81	58.30
Combined average and interpolated HV (6 - 12)	70.56	51.90	47.52	46.32	57.31	67.41	54.67	44.91	42.05	50.96

Note: For the purposes of this case study, it would have been beneficial to split the vehicle categories into mutually exclusive groups by vehicle type, eg:

- Light Vehicles (Classes 1 – 2)
- Rigid Medium Vehicles (Classes 3 – 5)
- Articulated Heavy Vehicles (Classes 6 – 12)

However, due to the aforementioned factors outside the control of this project, this data was not available.

Given that the traffic composition at RB1 is predominantly light vehicles (eg approx. 20% of total traffic is Classes 3 – 12) it has been assumed that the 85th percentile speeds for the All Vehicles category can essentially be construed as Light Vehicles only (Classes 1 – 2). Additionally, given that only approx. 6% of the traffic composition is Heavy Vehicles (Classes 6 – 12), it has been assumed that the Medium and Heavy Vehicles category can essentially be construed as Medium Vehicles only (Classes 3 – 5)

3.3.4 Travelled Path Analysis

The travelled path of a 19m Semi-trailer, travelling northbound in the outside lane, was simulated using Autoturn V10 software, in combination with Autocad 2018 drafting software.

This vehicle was the most common heavy-vehicle type witnessed on the 2019 site visit, and these vehicles were mostly witnessed using the outside lane to negotiate the roundabout.

Video recordings were captured using a "GoPro 5 Session" video camera, mounted to the windscreen at driver eye-height in a 2018 Toyota Camry passenger car. By waiting for a heavy vehicle to approach the roundabout, and then driving behind the heavy vehicle, the travelled path of the rear of the trailer was able to be clearly captured on video, shown below in Figure 28:

Figure 28 – GoPro screen capture at roundabout entry
Source: Google Streetview (2018)

The Autoturn simulation was calibrated by comparing the Autoturn vehicle paths with the videos recorded on site during the 2019 site visit, and adjusting the Autoturn to suit, until a reasonable match was achieved (ie within 200mm, by eye) between the videos and the Autoturn, with respect to where the rear wheels were in relation to edge lines etc, depicted below in Figure 29:

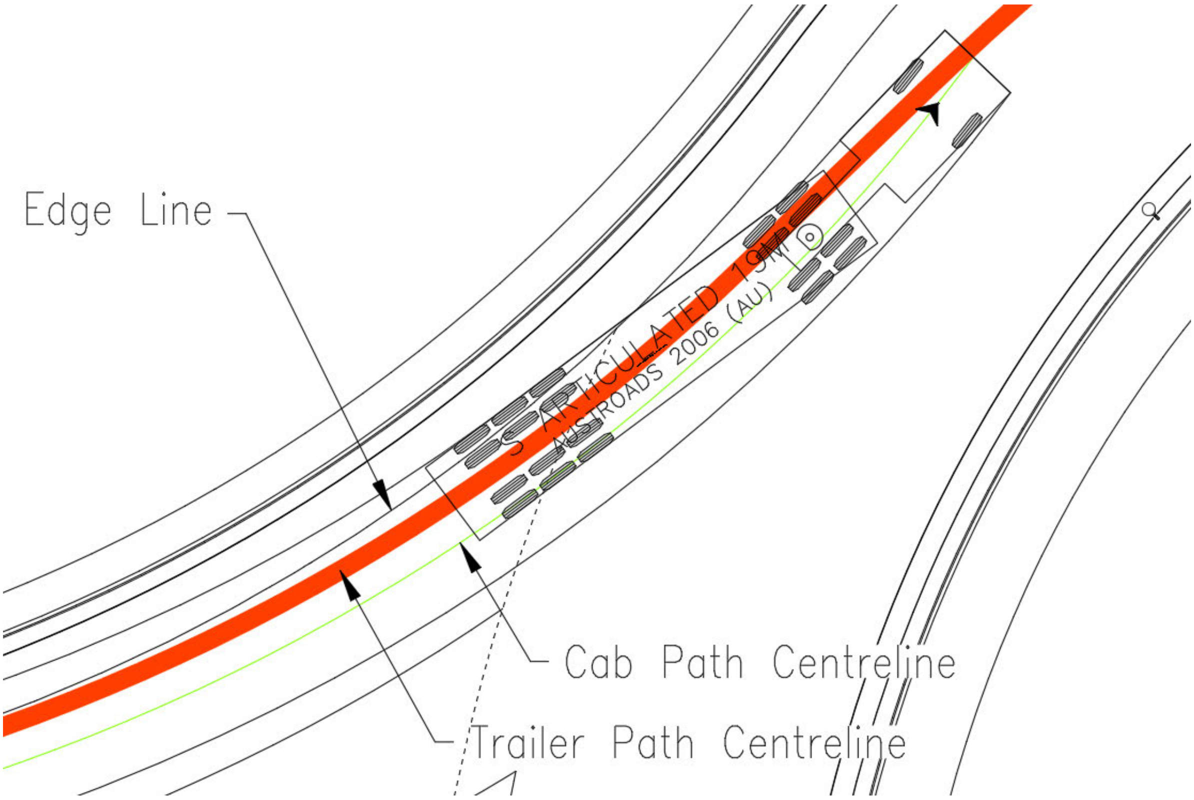


Figure 29 – AutoTURN path example at roundabout entry

Once the AutoTURN path was complete, the centre of the rear wheel paths were traced in AutoCAD using a series of arcs and straights (tangents). This particular approach was chosen because the rear wheels of the trailer trace a significantly different path to the cab, for example the cab essentially follows the centre of the lane, where-as the rear of the trailer tracks inside of this, on curves.

The path that the rear wheels travels is therefore "gentler" than the cabs, that is the rear trailer wheels typically describe larger arcs through the reverse curves, however it is assumed that a loaded trailer is less stable than the cab, therefore this path has been chosen so as to carry out a review of the critical path.

With the travelled path analysis complete, the horizontal geometry that the heavy vehicles follow, eg the straights and curves, could then be recorded and input into the coefficient of side friction analysis.

3.3.5 Crossfall analysis

The travelled centre-line path described above was then bought into 12D V12 Civil Design software package. The centre-line was offset left and right 1.25m, which is where the left and right rear wheels track in relation to the centre of the axle, for a typical 19m Semi-Trailer.

The as-constructed 12D model of the roundabout was supplied by the road authority designers, and all 3 strings mentioned above were draped onto the design tin.

Figure 30 shows the vertical and horizontal geometry reported in the long section, which is from the centre string, and the horizontal geometry in the plan view shows the original design control line. For a full size drawing of Figure 30, refer to Appendix G.

A crossfall report was generated, and super-elevation diagram plotted at the bottom of the long section.

The crossfall is measured in a straight line between the left and right wheels, ie varying axis, as would be experienced by a live axle vehicle.

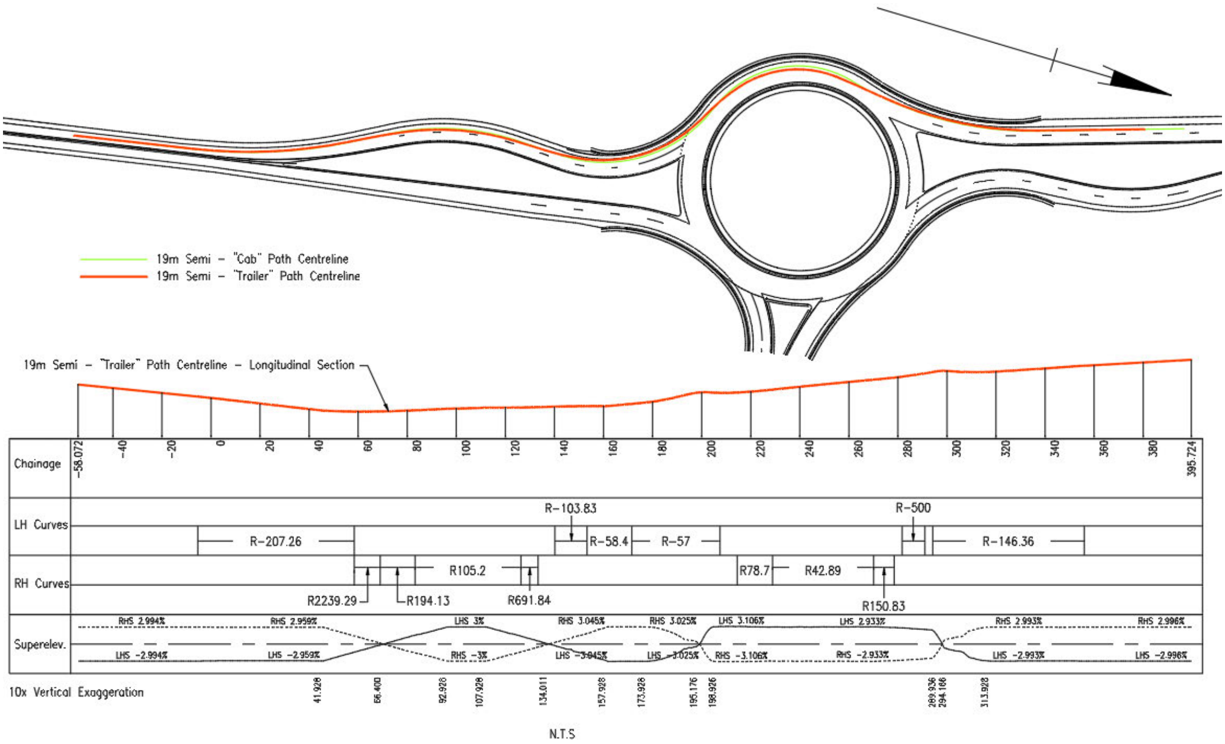


Figure 30 – RB1 – Geometry Review Plan and Long Section

With the crossfall analysis complete, the crossfalls that the heavy vehicles negotiate could then be recorded and input into the coefficient of side friction analysis.

3.3.6 Rate of rotation analysis

The works described above allowed the rate-of-rotation to be analysed and reported, including a plot of the values against the road geometry information. The rate-of-rotation is the rate of change in crossfall, expressed as percentage of crossfall per second. This can be viewed diagrammatically on the long section plot in Appendix G, with maximum values noted.

3.3.7 Coefficient of Side Friction analysis

The measured crossfall, along with the reported radius at 5m chainage intervals, was then output into excel, and the speed survey data added.

With speed, radius, and crossfall known, coefficient of side friction (f) could then be calculated, using Equation 10 of Austroads (2016):

$$f_1 = \frac{V^2}{127R} - e_{1\ \mathrm{rounded}}$$

Where:

f = side friction factor

V = speed (km/h)

R = curve radius

e = carriageway crossfall

The calculated side frictions were then compared to the maximum recommended side frictions as per Austroads (2015a). Maximum recommended values decrease as the speed increases, and maximum truck values are typically lower than maximum car values.

Therefore, a lookup table was created in excel, with linear interpolation employed between known values.

For All Vehicles (Classes 1 -12), absolute maximum car values were used, and for all other vehicle categories, absolute maximum truck values were used.

3.3.8 ARNDT Analysis

The roundabout geometry was also analysed using the ARNDT (A Roundabout Numerical Design Tool) software, which is freely available from the DTMR-QLD website. As mentioned in Section 2.9.3, this program is based on the work of Dr Owen Arndt, and his papers Arndt (1998) and Arndt (2001).

The ARNDT software is used to predict vehicle speeds on the various roundabout geometric elements, and also predicts crash rates based on relative speeds (eg entering speed vs circulating speed) and deceleration rates (ie desirable less than 20km/h deceleration between successive curves).

In order to carry out this analysis, the following data was required to be entered into the ARNDT software:

- Traffic Volumes
- Design Speeds on approach legs
- Roundabout geometry, eg curve radii and lengths, angle of leg separation, number of lanes

Interestingly, lengths of straights is not able to be entered, nor is crossfall, and neither of these elements is considered by the ARNDT software.

The required data was obtained from the road authority, and entered into the program.

Examples of the inputs are shown below in Figures 31 to 33:

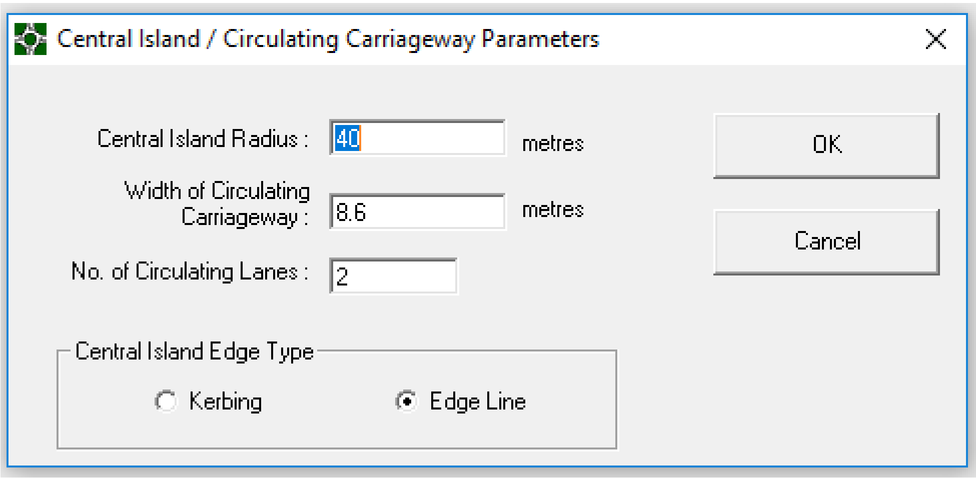


Figure 31 – ARNDT Example Input – Central Island Details

Source: ARNDT (2014)

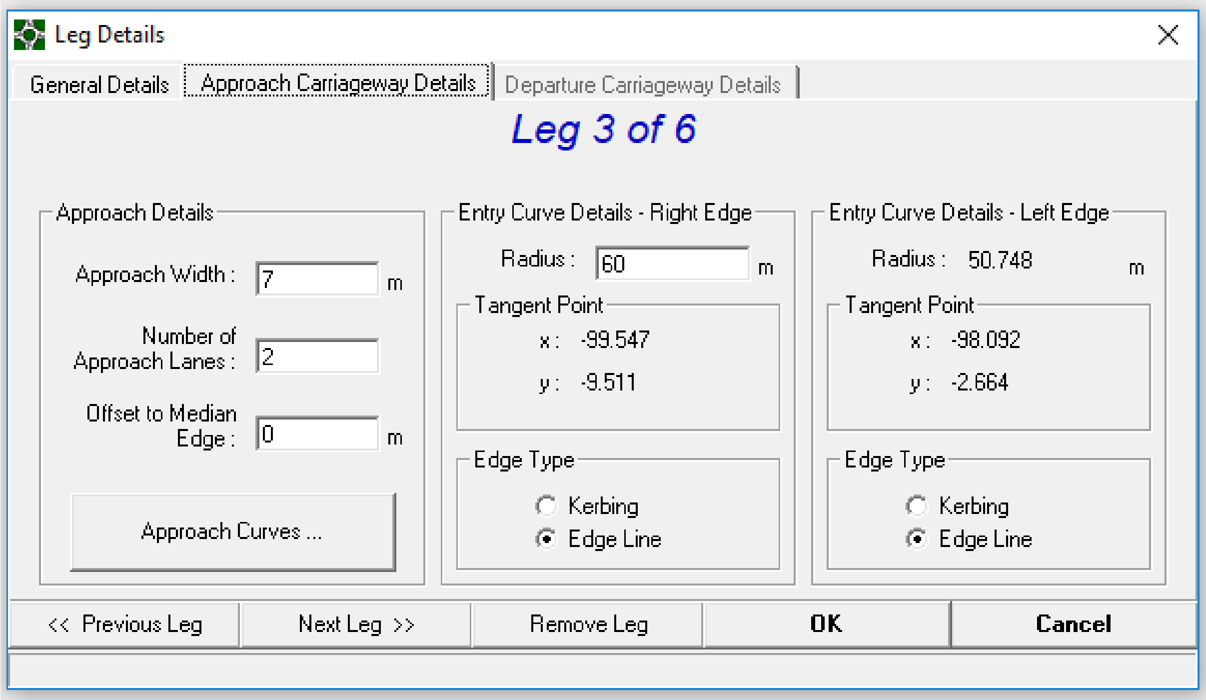


Figure 32 – ARNDT Example Input – Leg Details

Source: ARNDT (2014)

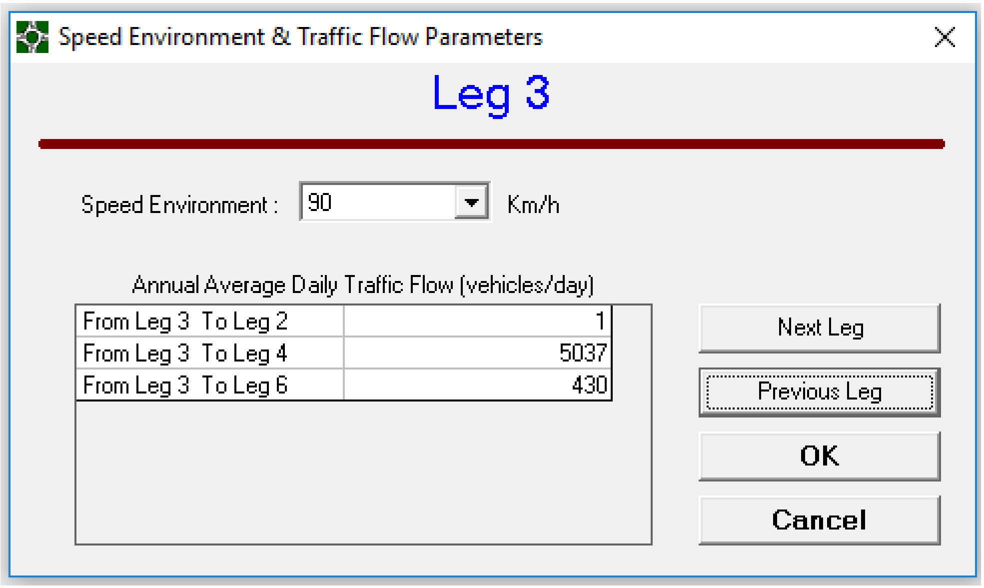


Figure 33 – ARNDT Example Input – Speed Environment & Traffic Flow Parameters

Source: ARNDT (2014)

An example of the outputs obtained from ARNDT are shown below in Figure 34:

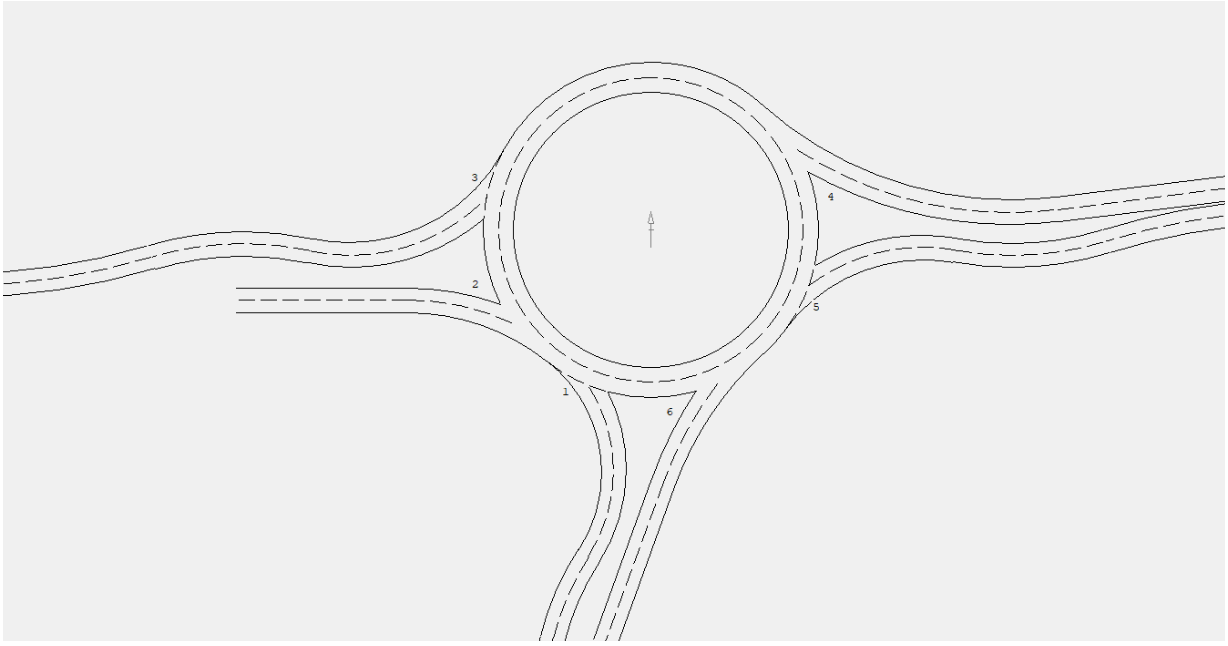


Figure 34 – ARNDT Example Output – Modelled Roundabout
Source: ARNDT (2014)

The ARNDT predicted speeds and travelled radii were output to Excel, and the coefficients of side friction calculated, in order to understand what criteria the software uses to predict vehicle speeds.

These calculated coefficients of side friction were also compared to the absolute maximum recommended values in Austroads (2015a).

A summary of the ARNDT predicted travelled radius, speeds, and calculated coefficients of side friction are shown below in Table 11:

Table 11 – RB1 ARNDT predictions and calculated coefficients of side friction

ARNDT Outputs and calculated side friction						
Curve	ARNDT Calculated Travelled Radius	Curve Direction	ARNDT Predicted Speed	Abs Max f	calc f	f difference
1	296.093	L	83.391	0.242	0.185	-0.057
2	120.656	R	74.637	0.290	0.364	0.074
3 (Entry)	61.322	L	61.95	0.328	0.493	0.165
4 (Circulating)	44.382	R	53.12	0.344	0.501	0.157
5 (Exit)	130.88	L	53.12	0.344	0.170	-0.174

3.4 Case Study – Roundabout 2 (RB2)

3.4.1 Methodology Introduction

RB2 is very similar to RB1 in terms of its geometry, speed environment, and traffic composition, being situated in close proximity to RB1, and, as per the case study introduction in Section 1.7.6, has experienced similar issues with heavy vehicle stability.

The road authority addressed these issues by reviewing the original signage design, in an effort to further warn heavy vehicle drivers to reduce their speed prior to entering the roundabout. Since the installation of the new signage, heavy vehicle roll over crashes have ceased. Before and after speed surveys were carried out in attempt to document the assumed effectiveness of the additional signage.

The analysis of the signage revisions, and before and after speed surveys is documented below.

3.4.2 Original Signage Design

The original signage design of RB2 consisted of the following signs on each approach:

- G1-5 Guide sign – approx. 150m before the give-way line
- W2-7 Roundabout Warning sign, with 50km/h W8-2 Advisory Speed sign – approx. 75m before the give-way line
- R1-3 Roundabout Give-Way sign – at the give-way line

The original sign types are shown below in Figures 31 – 33:

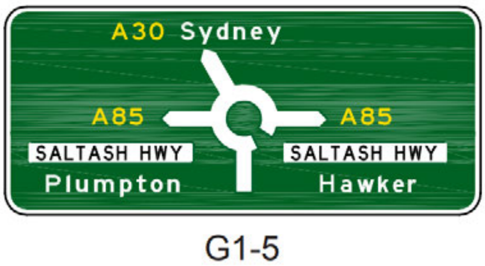


Figure 35 – RB2 – G1-5 Guide Sign
Source: MUTCD (2018)

Figure 36 – RB2 – W2-7 and W8-2 Roundabout Warning and Advisory Speed signs

Source: Google Streetview (2019)

Figure 37 – RB2 – R1-3 Roundabout Give-way sign

Source: Google Streetview (2019)

The G1-5 and R1-3 are standard recommended signs at large roundabouts, as per MUTCD (2018).

The W2-7 and W8-2 signs can be considered supplementary signs, recommended when the presence of a roundabout is not readily apparent to an approaching driver, as per MUTCD (2018).

3.4.3 2015 Speed Survey and Revised Signage Design

In 2015, following two heavy vehicle roll-over crashes, which were considered by the road authority to be potentially attributed to excess speed, a speed survey was carried out.

This speed survey was implemented at two locations, shown below in Figure 38, and was carried out via MetroCount tube counter method over a duration of ten days, for all vehicle classes (1 – 12).

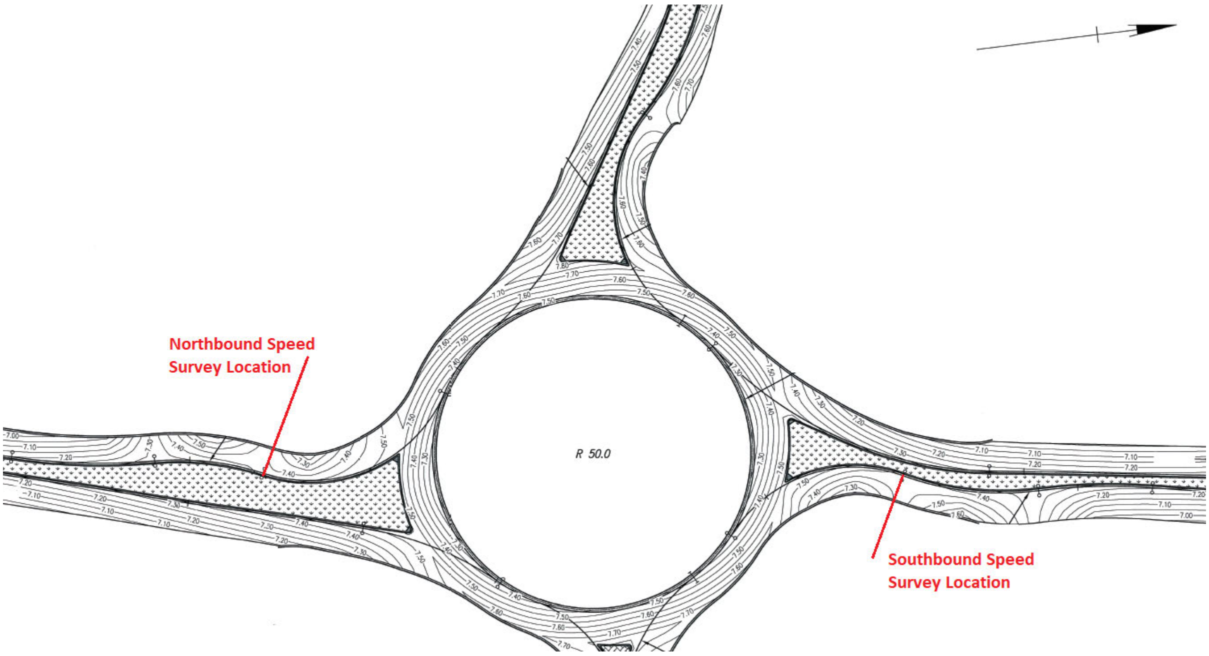


Figure 38 – RB2 – Speed Survey Locations
Source: Road Authority

Following a review of the 2015 surveyed speeds by the road authority, it was decided to amend the original signage design, by adding additional supplementary warning signage, both static and Vehicle Activated Signage (VAS), in advance of the roundabout approaches, to help convey the message that heavy vehicles need to reduce their speed before negotiating the roundabout and its approaches.

The signage revisions made were as follows:

- The W8-2 50km/h Advisory Speed sign was removed, and the W2-7 relocated further back from the give-way line, to approx. 250m before the give-way line
- Addition of a combined W1-8 Truck Tilting sign, W2-7 Roundabout Warning sign, G9-9 Reduce Speed sign, and W8-2 30km/h Advisory Speed sign, at approx. 185m before the give-way line
- Addition of an electronic Vehicle Activated Sign (VAS) featuring a flashing W2-7 Roundabout Warning sign, and a “Slow Down” sign, at approx. 80m before the give-way line

The revised and additional signs are shown below in Figures 39 to 41:

Figure 39 – RB2 – Relocated W2-7 Sign

Source: Google Streetview (2019)

Figure 40 – RB2 – Additional W1-8, W2-7, G9-9 and W8-2 signs

Source: Google Streetview (2019)

Figure 41 – RB2 – Additional Vehicle Activated Signage
Source: Google Streetview (2019)

3.4.4 Post sign installation crash history and 2019 Speed Survey

Following the installation of this signage, reviewing the available crash history reveals that there have been no heavy vehicle crashes at RB2 attributed to vehicle stability and/or roll overs.

A second speed survey was carried out by the road authority in 2019, in an effort to evaluate and document the apparent effectiveness of the supplementary warning signage.

The 2019 speed survey was carried out at the same two locations as the 2015 survey, over a 7 day period, via MetroCount tube counter method, for all vehicle classes (1 – 12).

Chapter 4 – Results and Discussion

4.1 Analysis and critical review of current standards, and development of recommendations – Results and Discussion

4.1.1 Central Island Radius and Circulating Carriageway Widths

Table 12 summarises the analysis and review of the current Austroads (2015a) central island radii and circulating carriageway widths for single lane roundabouts:

Table 12 – Analysis of Austroads (2015a) central island radii and circulating carriageway widths for single lane roundabouts

Desired driver speed on the fastest leg prior to the roundabout (km/h)	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)	Right Turn/Circulating Radius (m)	Desired Right Turn Speed (20km/h decrease)	f (3% Super)	f (3% adverse)	Abs max f
40	10	8	16.25	20	0.16	0.22	0.25
50	11	7.8	17.05	30	0.39	0.45	0.25
60	12	7.6	17.85	40	0.68	0.74	0.25
70	18	6.7	22.95	50	0.83	0.89	0.25

With respect to the table above, the following are important to note:

- Data shown in columns 1 – 3 are derived directly from Austroads (2015a) Tables 4.1 and 4.3
- The right-turn radii in Column 4 were calculated by adding columns 2 and 3, and then subtracting 1.75m, which is half the width of a 2.5m wide heavy vehicle, plus a 0.5m clearance. This gives the maximum radius that a heavy vehicle can follow when negotiating the roundabout
- Column 5 is calculated by subtracting 20km/h from Column 1. 20km/h is the desirable decrease in speed as per Austroads (2015a)
- With radii and speeds known, typical crossfalls are assumed, for superelevated and adverse crossfall scenarios, and associated side friction factors are calculated, shown in columns 6 and 7
- Values in column 8 are based on Austroads (2016) Table 7.5, absolute maximum recommended side friction factor for heavy vehicles, for the speeds calculated in column 5

As shown, for all but the 40km/h approach speed scenario, the coefficients of side friction required for a heavy vehicle to negotiate the roundabouts is well above the maximum recommended side friction factors.

4.1.2 Development of recommended central island radii and circulating carriageway widths

Table 13 summarises the recommended central island radii and circulating carriageway widths for single lane roundabouts to suit 19m Semi-Trailer:

Table 13 – Recommended central island radii and circulating carriageway widths for single lane roundabouts to suit 19m Semi-Trailer

Circulating Carriageway Type	Desired driver speed on the fastest leg prior to the roundabout (km/h)	Right Turn/Circulating Speed (km/h)	Circulating Carriageway Crossfall (%)	Coefficient of side friction (f)	Min. Right Turn/Circulating Radius (m)	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)
Super	40	15	2	0.3	5.5	10	8
	50	23	2	0.3	13.0	11	7.8
	60	32	2	0.3	25.2	22	6.4
	70	40	2	0.3	39.4	36	5.4
Adverse	40	15	-2	0.2	9.8	10	8
	50	23	-2	0.2	23.1	19	6.6
	60	32	-2	0.2	44.8	42	5.0
	70	40	-2	0.2	70.0	68	4.5

With respect to the table above, the following are important to note:

- Data shown in column 3 is based on desirable 20km/h speed decrease between entry curve and right turn, plus an additional heavy vehicle speed decrease in line with Austroads (2016) Part 3 Section 3.7 and Table 3.5.
- Recommended crossfall for superelevated scenarios is 2%, to reduce issues associated with superelevated transitions between entry curve and circulating carriageway
- Recommended superelevated side friction factor f = 0.3 as per Section 3.2.2
- Recommended adverse crossfall is 2%, to provide further distance between heavy vehicle centre of gravity and rollover hinge point than 3% crossfall, in line with Austroads (2016) Appendix B, Section B.3.
- Recommended adverse side friction factor f = 0.2 as per Section 3.2.2

As shown, the resulting desirable central island radii are considerably larger than those of Austroads (2015a).

Direct comparison is shown below in Table 14:

Table 14 – Comparison of recommended central island and circulating carriageway criteria to Austroads (2015a)

Desired driver speed on the fastest leg prior to the roundabout (km/h)	Recommended (2% Super)		Recommended (2% Adverse)		Austroads (2015a)	
	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)
40	10	8	10	8	10	8
50	11	7.8	19	6.6	11	7.8
60	22	6.4	42	5.0	12	7.6
70	36	5.4	68	4.5	18	6.7

4.1.3 Current reverse curve approach geometry examples

Tables 15 and 16 summarise the analysis and critical review of the current Austroads (2015a) reverse curve approach geometry example:

Table 15 – Analysis and critical review of the current Austroads (2015a) reverse curve approach geometry example – curve radii

Austroads (2015a) Figure 4.4					
Curve #	**Operating Speed (km/h)**	**Crossfall (%)**	**Radius**	**f**	**Abs max f**
Curve 1	100	3	460.000	0.141	0.12
Curve 2	80	-3	200.000	0.282	0.20
Curve 3 (Entry)	60	3	55.000	0.485	0.24
Curve 4 (Circulating)	40	-3	32.000	0.424	0.25

With respect to the table above, the following are important to note:

- Operating speeds and crossfalls are generally derived straight from Austroads (2015a) Figure 4.4
- Operating speed for Curve 4 is assumed, based on desirable maximum 20km/h speed decrease from preceding curve
- Crossfall for Curve 4 is assumed, based on common practise in QLD
- The actual travelled path radii for curves 1 and 2 is ignored due to negligible effect on results due to the large radii of the curves
- Curve 3 radius is set to R55, which is the maximum entry path radius as per Austroads (2015a)
- Curve 4 radius is as per Austroads (2015a) Figure 4.4 central island radius, with an additional 2.0m to allow for tracking of a 19m Semi-Trailer

As shown, very high coefficients of side friction are required for vehicles to negotiate the geometry at the intended operating speeds.

As shown in the literature review, a critical design element with respect to heavy vehicle operation on reverse-curve roundabout approaches is the lengths of straights (tangents) provided between curves, due to the tracking of heavy vehicles, and to allow drivers sufficient distance to react and decelerate between curves.

Table 16 summarises the analysis and critical review of the tangent lengths provided by the Austroads (2015a) reverse curve approach geometry example:

Table 16 – Analysis and critical review of the current Austroads (2015a) reverse curve approach geometry example – tangent length

Austroads (2015a) Figure 4.4						
Curve #	Operating Speed (km/h)	Decrease in speed between curves (km/h)	Tangent Length Specified (m)	Deceleration Length Required (m)	Average Speed Between Curves (km/h)	0.7V (m)
Curve 1	100					
Curve 2	80	20	0.7V	49	90	63
Curve 3 (Entry)	60	20		38	70	49
Curve 4 (Circulating)	40	20		27	50	35

The decrease in speed between curves is 20km/h, which meets the desirable criteria of Austroads (2015a) and ARNDT.

The tangent lengths are not shown or specified on the Austroads (2015a) reverse curve approach geometry example, however in the notes below the example, designers are referred to the reverse-curve guidelines in the Austroads (2016) document. In this document, the following guidance is provided: "When providing for trucks, the reverse curves should be joined by a tangent at least 0.7 V m long or spirals to allow for the tracking of these large vehicles. Where deceleration is required on the approaches to a lower radius curve, sufficient distance must be provided to enable the drivers to react and decelerate."

As shown in Table 16, if the guidance of Austroads (2016) is followed, then tangent lengths of 0.7V will be provided, shown in column 7, which are longer than the deceleration lengths calculated in column 5.

Tables 17 and 18 summarise the analysis and critical review of the MRWA (2019a) example:

Table 17 – Analysis and critical review of the current MRWA (2019a) – curve radii

MRWA (2019a) Drawing No. 200331-0203-7 - Variant 1 - 90km/h					
Curve #	Operating Speed (km/h)	Crossfall (%)	Radius	f	Abs max f
Curve 1	90	3	415.000	0.124	0.12
Curve 2	70	-2	225.000	0.191	0.20
Curve 3 (Entry)	50	3	55.000	0.328	0.24
Curve 4 (Circulating)	30	-3	50.000	0.172	0.25

With respect to the table above, the following are important to note:

- Operating speeds and crossfalls are generally derived straight from MRWA (2019a) Drawing No. 200331-0203-7
- Operating speed for Curve 4 is assumed, based on desirable maximum 20km/h speed decrease from preceding curve
- Crossfall for Curve 4 is assumed, based on preference of MRWA (2019a) Table 4.10.1
- The actual travelled path radii for curves 1 and 2 is ignored due to negligible affect on results due to the large radii of the curves
- Curve 3 radius is set to R55, which is the maximum entry path radius as per Austroads (2015a)
- Curve 4 radius is as per desirable minimum R50 as per MRWA (2019a) Drawing No. 200331-0203-7

As shown, a very high coefficient of side friction is required for vehicles to negotiate the entry curve at the intended operating speeds.

Table 18 summarises the analysis and critical review of the tangent lengths provided by the MRWA (2019a) example:

Table 18 – Analysis and critical review of the MRWA (2019a) reverse curve approach geometry example – tangent length

MRWA (2019a) Drawing No. 200331-0203-7 - Variant 1 - 90km/h						
Curve #	Operating Speed (km/h)	Decrease in speed between curves (km/h)	Tangent Length Specified (m)	Deceleration Length Required (m)	Average Speed Between Curves (km/h)	0.7V (m)
Curve 1	90		-			
Curve 2	70	20	10 - 20	43	80	56.000
Curve 3 (Entry)	50	20	10 - 20	33	60	42.000
Curve 4 (Circulating)	30	20	0	22	40	28.000

The intended decrease in speed between curves is 20km/h, which meets the desirable criteria of Austroads (2015a) and ARNDT, however the tangent lengths specified are considerably shorter than both the deceleration lengths required, and the 0.7V requirement.

Tables 19 and 20 summarise the analysis and critical review of the FDOT (2019) example:

Table 19 – Analysis and critical review of the current FDOT (2019) – curve radii

FDOT - Exhibit 213-2 - 55mph					
Curve #	**Operating Speed (km/h)**	**Crossfall (%)**	**Radius**	**f**	**Abs max f**
Curve 1	88	2	427.000	0.123	0.12
Curve 2	68	-2	244.000	0.169	0.20
Curve 3 (Entry)	40	2	55.000	0.209	0.24
Curve 4 (Circulating)	20	-2	18.910	0.187	0.25

Notes:

- Operating speed for Curve 1 is derived straight from FDOT (2019) Exhibit 213-2
- Crossfalls are generally derived straight from FDOT (2019) Section 213.3.1
- Operating speed for Curve 2 is assumed, based on Austroads (2015a) desirable maximum 20km/h speed decrease from preceding curve
- Operating speed for Curve 3 is based on the text in FDOT (2019) Section 213.3.1, where it is mentioned that it is assumed that for Curve 3, the driver has decelerated to an operating speed between 20 and 25mph
- Operating speed for Curve 4 is assumed, based on Austroads (2015a) desirable maximum 20km/h speed decrease from preceding curve
- Crossfall for Curve 4 is assumed, based on FDOT (2019) Section 213.3.7
- The actual travelled path radii for curves 1 and 2 is ignored due to negligible effect on results due to the large radii of the curves
- Curve 3 radius is set to R55, which is the maximum entry path radius as per Austroads (2015a)
- Curve 4 radius is based on the upper range of values given on FDOT (2019) Exhibit 213-2

As shown, the coefficients of side friction are generally equal to or less than the absolute maximum values of Austroads (2016).

Table 20 summarises the analysis and critical review of the tangent lengths provided by the FDOT (2019) example:

Table 20 – Analysis and critical review of the FDOT (2019) reverse curve approach geometry example – tangent length

FDOT - Exhibit 213-2 - 55mph						
Curve #	Operating Speed (km/h)	Decrease in speed between curves (km/h)	Tangent Length Specified (m)	Deceleration Length Required (m)	Average Speed Between Curves (km/h)	0.7V (m)
Curve 1	88		-			
Curve 2	68	20	31	42	78	54.600
Curve 3 (Entry)	40	28	15	41	54	37.800
Curve 4 (Circulating)	20	20	0	16	30	21.000

As shown, the intended decrease in speed between curve 2 and 3 is greater than the desirable criteria of Austroads (2015a) and ARNDT. Additionally, the tangent lengths specified are considerably shorter than both the deceleration lengths required, and the 0.7V requirement.

4.1.4 Development of recommended reverse curve approach geometry

Table 21, and Figure 42 below show the recommended reverse curve approach geometry for a 90km/h scenario:

Table 21 – Recommended reverse curve approach geometry – 90km/h

Curve #	Operating Speed (km/h)	Crossfall (%)	f	Travelled Path Radius (m)	Deceleration length required between curves (m)	Average Speed Between Preceeding Curve - V (km/h)	Length of Straight Required Between Preceeding Curve (0.7V) (m)
Curve 1	90	2	0.150	375.2		-	-
Curve 2	70	-2	0.153	289.4	43.4	80.0	56.0
Curve 3 (Entry)	50	2	0.250	72.9	32.6	60.0	42.0
Curve 4 (Circulating)	30	-2	0.200	39.4	21.7	40.0	28.0

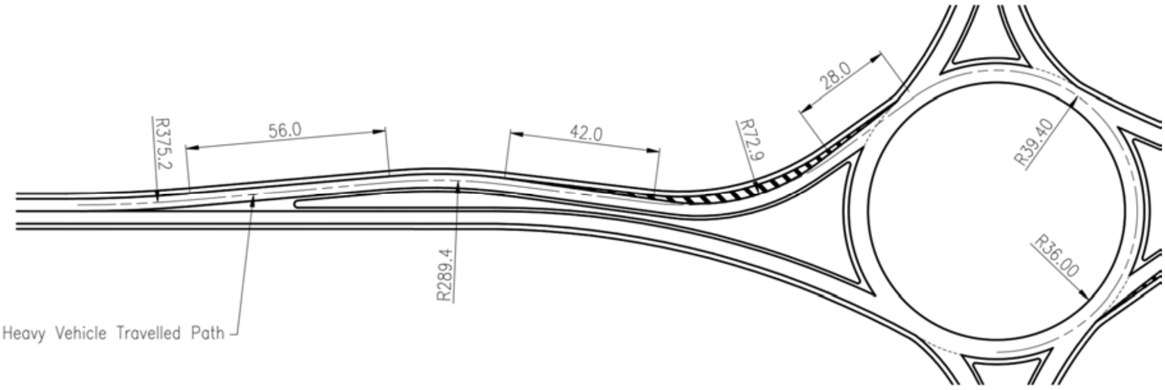


Figure 42 – Recommended reverse curve approach geometry – 90km/h

Table 22 shows the ARNDT predicted accident totals for the original RB1 geometry:

Table 22 – ARNDT predicted accident totals – Original RB1 Geometry

Leg Number	Approaching Rear-End	Entering/Circulating	Single Vehicle	SideSwipe	Exiting/Circulating	Other	Total
1	0.04232	0.03726	0.15451	0.01101	0.00000	0.01488	0.25998
2	0.00000	0.00000	0.00000	0.00000	0.01191	0.00000	0.01191
3	0.09278	0.03444	0.21019	0.02273	0.00000	0.02346	0.38360
4	0.00000	0.00000	0.00000	0.00000	0.01748	0.00000	0.01748
5	0.04137	0.02028	0.20449	0.03753	0.00000	0.03214	0.33581
6	0.00000	0.00000	0.00000	0.00000	0.04306	0.00000	0.04306
Total:	**0.17647**	**0.09197**	**0.56918**	**0.07128**	**0.07246**	**0.07048**	**1.05184**

Table 23 shows the ARNDT predicted accident totals for the modified RB1 geometry, using the recommended geometry described above:

Table 23 – ARNDT predicted accident totals – Modified RB1 Geometry

Leg Number	Approaching Rear-End	Entering/Circulating	Single Vehicle	SideSwipe	Exiting/Circulating	Other	Total
1	0.04238	0.06300	0.14834	0.01111	0.00000	0.01488	0.27970
2	0.00000	0.00000	0.00000	0.00000	0.01158	0.00000	0.01158
3	0.12749	0.00000	0.21500	0.01608	0.00000	0.02346	0.38202
4	0.00000	0.00000	0.00000	0.00000	0.01663	0.00000	0.01663
5	0.05672	0.00318	0.18491	0.02482	0.00000	0.03214	0.30178
6	0.00000	0.00000	0.00000	0.00000	0.00031	0.00000	0.00031
Total:	**0.22658**	**0.06618**	**0.54824**	**0.05201**	**0.02852**	**0.07048**	**0.99202**

As shown, the accident rates for all accident types apart from the "Approaching Rear-End" type have reduced.

Table 24 shows an additional ARNDT output, specifically for the approaching rear-end accident types, for the original RB1 geometry:

Table 24 – ARNDT approaching rear-end accident output – Original RB1 Geometry

Leg No.	Approaching Traffic Flow (veh/d) Qa	Circulating Traffic Flow adjacent to the Entry (veh/d) Qci	Number of Approach Lanes Na	Speed Environment (km/h) SE	Entry Path Radius (m) Ra	85th percentile Entry Speed (km/h) Sa	Accident Rate (acc/yr) Ar	Accident Cost ($/yr)
1	3469	4790	2	90	50.369	56.585	0.04232	1253
3	5468	3115	2	90	61.322	61.951***	0.09278	2746
5	7492	432	2	90	62.789	62.456***	0.04137	1225
						Total:	**0.17647**	**5224**

Table 25 shows the same output, for the modified RB1 geometry:

Table 25 – ARNDT approaching rear-end accident output – Modified RB1 Geometry

Leg No.	Approaching Traffic Flow (veh/d) Qa	Circulating Traffic Flow adjacent to the Entry (veh/d) Qci	Number of Approach Lanes Na	Speed Environment (km/h) SE	Entry Path Radius (m) Ra	85th percentile Entry Speed (km/h) Sa	Accident Rate (acc/yr) Ar	Accident Cost ($/yr)
1	3469	4790	2	90	50.396	56.601	0.04238	1254
3	5468	3115	2	90	75.003	66.219***	0.12749	3774
5	7492	432	2	90	76.840	66.727***	0.05672	1679
						Total:	**0.22658**	**6707**

As shown, the accident rates are directly related to the predicted speed on the entry curve, which in turn is directly related to the entry path radius. Both versions of the geometry feature entry path radii larger than the maximum 55m, and both result in entry speeds above the maximum desirable limit of 60km/h.

The larger entry path radii of the modified geometry is required due to the heavy vehicle's lower tolerance of side friction. As shown in Table 21, the actual predicted speed on the entry curve for a heavy vehicle is 50km/h, because the heavy vehicle driver, given appropriate warning and sufficient braking distance, will drive the curve at a maximum side friction value of f = 0.25.

The ARNDT software on the other hand, as shown in the literature review, considers light vehicles only, and assumes that a side friction value of f = 0.5 will be generated by drivers on the entry curve, giving a significantly higher predicted speed than that of a heavy vehicle.

Therefore, a unique approach line-marking treatment was developed, based on the principles of the maximum entry path radii concept of Austroads (2015a). The development process is described below in Figure 43:

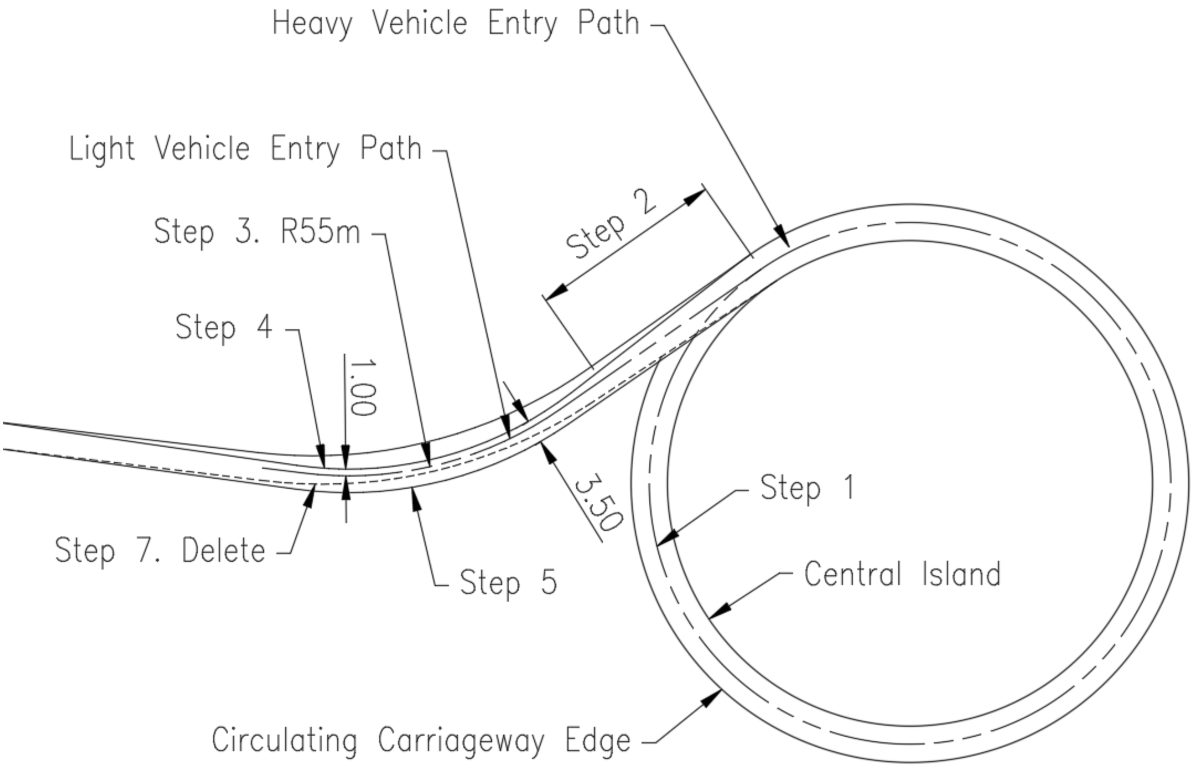


Figure 43 – Recommended Approach Line-marking development process

Notes:

1. Offset the central island circle at half the width of the circulating carriageway. This is the path that a light vehicle will take when circulating the roundabout, in line with Section 4.5.3
2. Draw a line tangential to the circle from Step 14 and the heavy vehicle path Entry Curve
3. Fillet the line from Step 15 to the line from Step 8 at a radius of 55m. This is the path that a light vehicle will take on the entry curve, in line with Section 4.5.3 - Maximum Entry Path Radius
4. Offset the arc from Step 16 1.0m to the inside. This will become the left hand edge line/chevron outline for the Entry Curve

5. Offset the arc from Step 17 3.5m to the outside. This will become the right hand edge line for the Entry Curve
6. Join the arcs from Steps 17 and 18 to the preceding edge line curves, and the central island and circulating carriageway edge using tangential lines
7. Delete the original right hand edge line of the entry curve, and associated preceding and following tangents

Following the above process gives the resulting line-marking, shown below in Figure 44 which provides entry path radii that results in desirable entry speeds for both light and heavy vehicles:

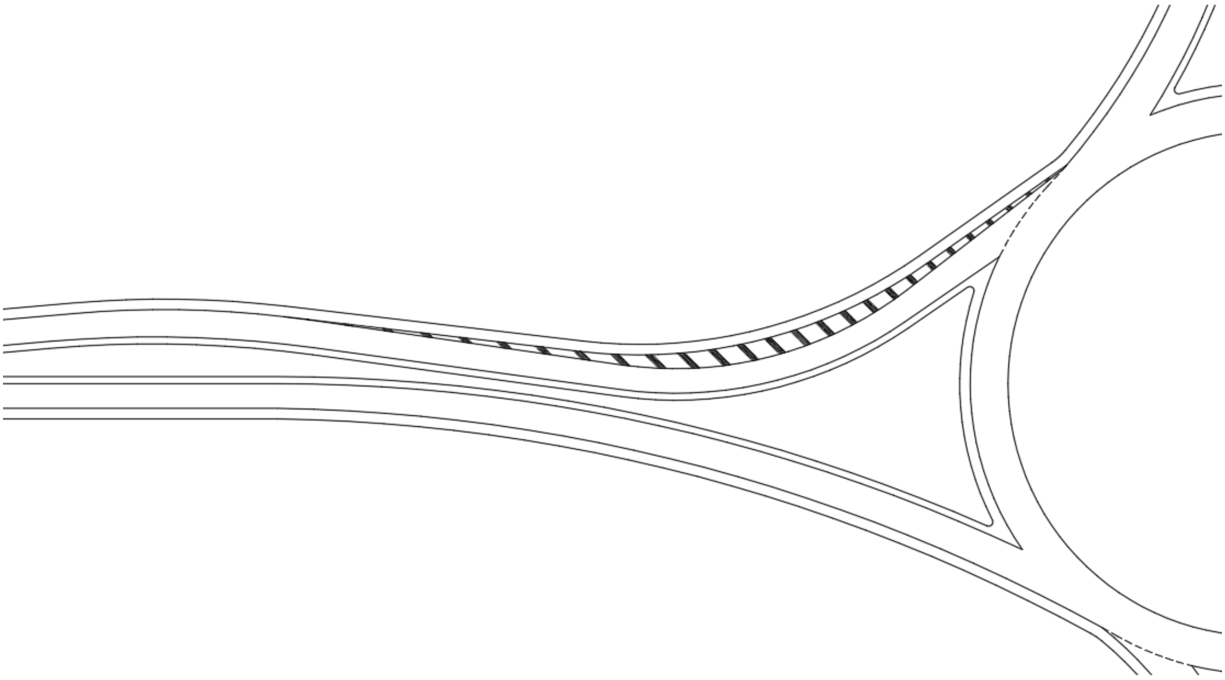


Figure 44 – Recommended Approach Line-marking

If the above described approach line-marking is adopted within the modified RB1 ARNDT analysis, the following accident rates shown in Table 26 can be assumed:

Table 26 – ARNDT predicted accident rates using recommended geometry including recommended approach line-marking

Leg Number	Approaching Rear-End	Entering/Circulating	Single Vehicle	SideSwipe	Exiting/Circulating	Other	Total
1	0.04232	0.06300	0.14834	0.01111	0.00000	0.01488	0.27965
2	0.00000	0.00000	0.00000	0.00000	0.01158	0.00000	0.01158
3	0.09278	0.00000	0.21500	0.01608	0.00000	0.02346	0.34732
4	0.00000	0.00000	0.00000	0.00000	0.01663	0.00000	0.01663
5	0.04137	0.00318	0.18491	0.02482	0.00000	0.03214	0.28642
6	0.00000	0.00000	0.00000	0.00000	0.00031	0.00000	0.00031
Total:	**0.17647**	**0.06618**	**0.54824**	**0.05201**	**0.02852**	**0.07048**	**0.94190**

4.1.5 Signage review

A typical signage layout at a large roundabout is shown below in Figure 45:

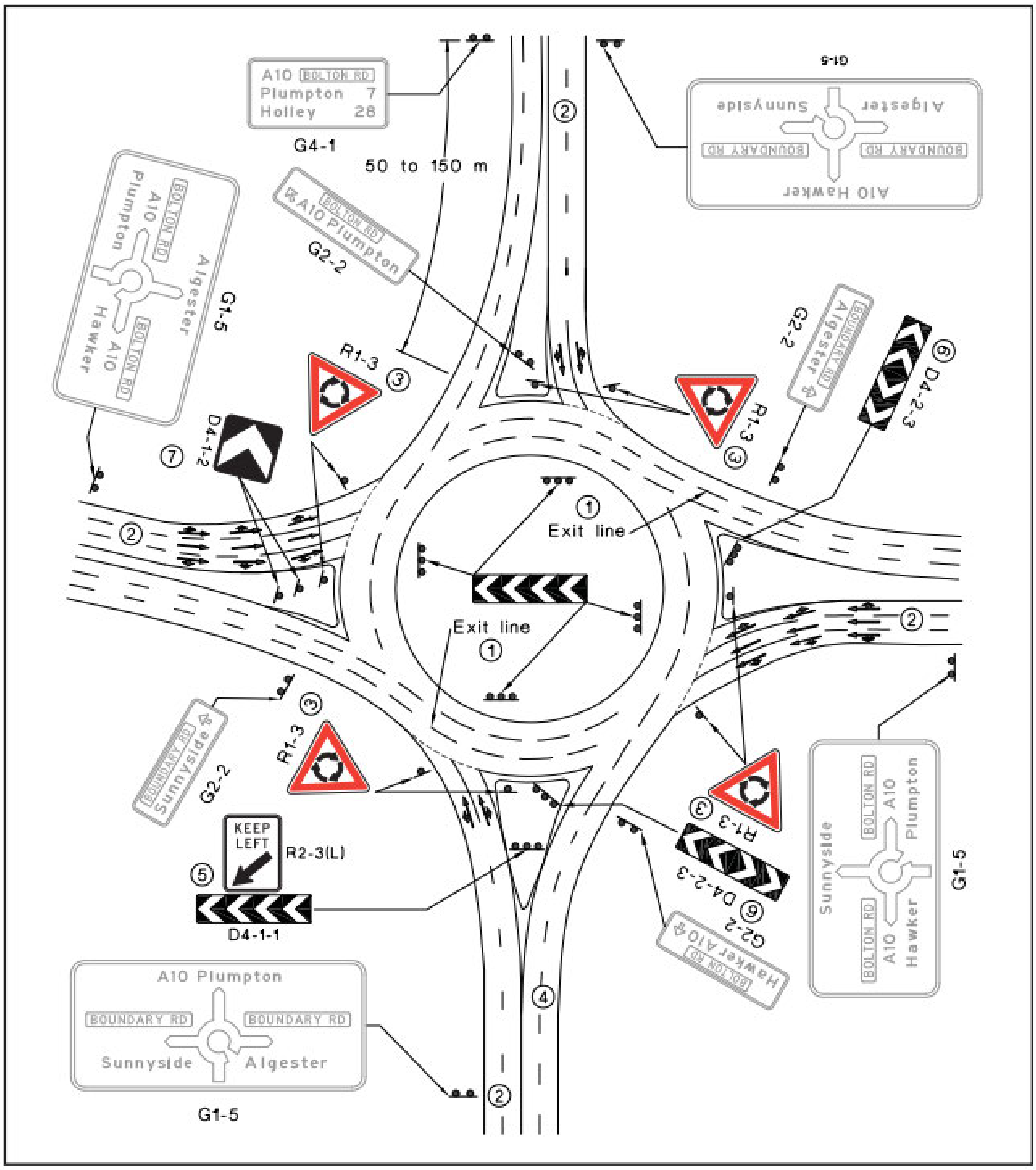


Figure 45 – Typical signage layout at large roundabout
Source: MUTCD (2018) Figure 2.7

As shown, additional considerations and recommendations for reverse-curve approaches are not provided.

Figure 46 shows a supplementary advisory speed information panel recommended in the DTMR-QLD (2019) document to be added to the G1-5 sign:

Figure 46 – Supplementary advisory speed information panel added to G1-5 sign
Source: TMR (2019) Figure 3(C)

As per the advice in the DTMR-QLD (2019) document, the advisory speed for a particular roundabout approach is recommended to be determined and displayed as the "safe" speed on the supplementary panel.

In addition to the above signs, and as per the literature review, it was found to be necessary to provide advanced warning to heavy vehicle drivers of the reverse-curve approaches to high-speed roundabouts, as these curves can be difficult to judge by said drivers, and can be "sub-standard" if inadequately judged.

MUTCD (2019) Section 4.4 outlines the recommended treatments for sub-standard horizontal curves, which are defined as horizontal curves where the advisory speed of the curve is at least 15km/h than the 85th percentile speed on the immediate preceding section of road.

For the purposes of this review, reverse-curves at roundabout approaches are considered to be sub-standard for heavy vehicles, and are to be treated in line with MUTCD (2019) Section 4.4, for the following reasons:

- Significant gap in horizontal curve capability of light vehicles vs heavy vehicles
- Decreased margin for error with respect to driver assessment of appropriate curve speed
- 20km/h speed decrease between curves

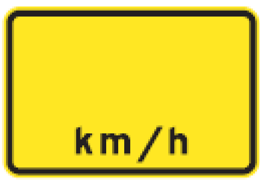
MUTCD (2019) Section 4.4.7 gives various options and warrants for signage treatment of substandard horizontal curves.

Table 27 summarises the signage options and warrants considered, and provides justification for the selection of the recommended sign:

Table 27 – Recommended Curve Warning Sign decision process summary

Source	Sign Face	Sign Code	Description	Warrants for use (MUTCD 2019)	Recommended for high-speed heavy vehicle approach?	Justification
MUTCD (2019)		W1-3	Curve	The Curve sign shall be used in advance of a substandard curve in accordance with Figure 4.5 (see Clause 4.4.4). The Advisory Speed sign (W8-2) shall be used in conjunction with this sign where indicated in Figure 3.5 (see also Clause 4.4.6) when used in advance of a substandard curve. It is also permissible to use this sign where, although the conditions specified in Clause 4.4.1 do not apply, the road geometry is such that the curve may not be readily perceived, e.g. where a crest precedes a horizontal curve (see Clause 4.4.7).	No	Whilst the warrants are technically met (eg to be used where the curve may not be readily percieved) it is necessary to warn heavy vehicle drivers of more than the one curve depicted on the sign.
MUTCD (2019)		W1-4	Reverse Curve	The Reverse Curve sign shall be used where two curves in opposite directions, one or both of which is substandard (see Clause 3.4.1), are separated by a tangent length of less than 120 m. The Advisory Speed sign (W8-2) shall be used in conjunction with this sign in accordance with Figure 4.5 (see Clause 4.4.4) when it is used in advance of one or more substandard curves, and shall indicate the advisory speed of the curve with the lower speed value (see Clause 4.4.6.2).	No	Whilst the warrants are technically met (eg tangents less than 120m), it is necessary to warn heavy vehicle drivers of more than only the two curves depicted in the sign.
MUTCD (2019)		W1-5	Winding Road	The Winding Road sign shall be used where there is a series of closely spaced curves some or all of which warrant the use of Turn (W1-1) or Curve (W1-3) signs. A Turn sign (W1-1) or a Curve sign (W1-3) together with an Advisory Speed sign (W8-2), when this is required by the provisions of Clause 4.4.1, shall be used after sign W1-5 to indicate the direction and speed value of the first substandard curve (see also Clause 4.4.6). The exception to this rule is where, in a distance of 1 km or less, there is a series of three or more closely spaced curves of similar speed value and the alignment of the first curve is adequately delineated, in which case the Advisory Speed sign (W8-2) may be used with the W1-5 sign and additional Turn or Curve signs need not be used. The left (L) or right (R) version of this sign should be selected according to the direction of the first curve.	Yes	The warrants are met as per sign W1-3, and a series of closely spaced curves is shown, which accurately depicts a reverse-curve approach to a roundabout.

As per MUTCD (2019), the recommended Winding Road (W1-5) sign is to be used with an Advisory Speed (W8-2) sign, shown below in Figure 47, with the advisory speed to equal the speed value of the first curve.



W8-2

Figure 47 – Advisory Speed (W8-2) sign

Source: MUTCD (2018) Section 4.4.7.7

This is not considered appropriate at reverse-curve roundabout approaches however, as this may give a false impression to drivers that one speed is appropriate for all approach curves, whereas in actual fact, significant speed reduction is required between all curves.

Therefore, the following sign, shown below in Figure 48, is recommended to be erected with the Winding Road (W1-5) sign:

G9-9

Figure 48 – Reduce Speed (G9-9) sign

Source: MUTCD (2018) Section 4.11.2.14

A further review of MUTCD (2019) was carried out, to determine what (if any) other signs may be appropriate to provide advanced warning to heavy vehicle drivers of the reverse-curve approaches to high-speed roundabouts,

The below extract, shown below in Figure 49, depicts a potential sign and associated warrants for use:

W1-8(L)

The Tilting Truck sign shall be used where there is a history of trucks toppling even where all other required curve warning and delineation devices are provided. It is normally associated with, and placed in advance of a curve or turn warning sign. The following curve survey speed table is used to calculate the appropriate advisory speed to be used with the Tilting Truck sign (W1-8):

Curve Survey Speed	Maximum Side Friction as a Function of 'g' 9.81m/s/s
≤ 40 km/h	0.20*
≤ 50 km/h	0.18
≤ 60 km/h	0.16
≤ 70 km/h	0.14
≤ 80 km/h	0.12
≤ 90 km/h	0.10

Figure 49 – Tilting Truck (W1-8) sign and warrants for use

Source: MUTCD (2018) Section 4.4.7.10

It is recommended to provide this sign prior to the circulating carriageway, with the advisory speed set to the safe circulating speed for heavy vehicles.

4.2 RB1 – Results and Discussion

4.2.1 RB1 – Crash History Results and Discussion

Review of the details in the reports, and anecdotal evidence provided by the relevant road authority engineers and designers, reveals that the crashes are exclusively occurring at, or are apparently contributed to by, the approach curve geometry.

4.2.2 RB1 - Calculated Side Friction Values

The primary focus for the results analysis centres on the calculated values for coefficients of side friction shown in the tables below, as it had been identified in the literature review that this criteria is a key indicator of heavy vehicle stability.

Tables 28 – 31 below show the calculated coefficients of side friction for the respective vehicle categories, and their comparison to the Austroads (2015a) values.

4.2.3 RB1 - All Vehicles (Classes 1 – 12) and ARNDT Side Friction Values

As shown in Table 28, coefficients of side friction being generated at RB1 for the All Vehicles category are well above the absolute maximum recommended values as per Austroads (2015a):

Table 28 – Calculated coefficients of side friction for All Vehicles (Classes 1 – 12)

All Vehicles (Classes 1 - 12)							
Chainage	Actual Travelled Radius	Curve Direction	Xfall	85 % Speed	Abs Max f	calc 85 % f	f difference
36	**207.26**	**L**	**3**	**79.236**	**0.265**	**0.209**	**-0.056**
41	207.26	L	3.000	78.186	0.270	0.202	-0.068
46	207.26	L	2.567	77.136	0.275	0.200	-0.075
51	207.26	L	1.967	76.086	0.280	0.200	-0.080
56			1.367	75.035	0.285		
61			0.767	73.985	0.295		
66			0.167	72.935	0.300		
71			-0.433	71.885	0.305		
76			-1.033	70.835	0.310		
81	105.2	R	-1.633	69.785	0.312	0.348	0.036
86	105.2	R	-2.233	68.734	0.314	0.331	0.017
91	105.2	R	-2.833	67.684	0.316	0.315	-0.001
96	105.2	R	-3.000	66.634	0.318	0.302	-0.016
101	**105.2**	**R**	**-3**	**65.584**	**0.320**	**0.292**	**-0.028**
106	105.2	R	-3.000	65.032	0.320	0.287	-0.033
111	105.2	R	-2.587	64.480	0.322	0.285	-0.037
116	105.2	R	-1.987	63.927	0.324	0.286	-0.038
121			-1.387	63.375	0.324		
126			-0.787	62.823	0.326		
131			-0.187	62.271	0.326		
136	103.83	L	0.413	61.718	0.328	0.285	-0.043
141	103.83	L	0.953	61.166	0.328	0.274	-0.054
146	103.83	L	1.619	60.614	0.330	0.262	-0.068
151	58.4	L	2.185	60.062	0.330	0.465	0.135
156	58.4	L	2.770	59.509	0.332	0.450	0.118
161	58.4	L	3.005	58.957	0.334	0.439	0.105
166	58.4	L	2.999	58.405	0.334	0.430	0.096
171	57	L	3.004	57.853	0.336	0.432	0.096
176	57	L	2.997	57.300	0.336	0.424	0.088
181	57	L	2.729	56.748	0.338	0.418	0.080
186	**57**	**L**	**2.173**	**56.196**	**0.338**	0.415	**0.077**
191	57	L	1.419	55.955	0.340	0.418	0.078
196	57	L	0.738	55.714	0.340	0.421	0.081
201	57	L	-0.336	55.473	0.340	0.428	0.088
206			-3.008	55.232	0.340		
211	78.7	R	-3.085	54.991	0.342	0.272	-0.070
216	78.7	R	-3.036	54.751	0.342	0.270	-0.072
221	78.7	R	-2.984	54.510	0.342	0.267	-0.075
226	42.89	R	-2.997	54.269	0.342	0.511	0.169
231	42.89	R	-2.985	54.028	0.342	0.506	0.164
236	42.89	R	-2.979	53.787	0.344	0.501	0.157
241	42.89	R	-2.983	53.546	0.344	0.497	0.153
246	**42.89**	**R**	**-3**	**53.305**	**0.344**	0.492	**0.148**
251	42.89	R	-2.987	54.055	0.342	0.507	0.165
256	42.89	R	-2.979	54.806	0.342	0.522	0.180
261	42.89	R	-2.983	55.556	0.340	0.537	0.197
266	42.89	R	-3.005	56.306	0.338	0.552	0.214
271	150.826	R	-2.996	57.057	0.336	0.140	-0.196
276			-2.985	57.807	0.336		
281	500	L	-2.866	58.558	0.334	0.083	-0.251
286	500	L	-2.698	59.308	0.332	0.082	-0.250
291	146.361	L	-2.012	60.058	0.330	0.214	-0.116
296	146.361	L	0.841	60.809	0.330	0.191	-0.139
301	146.361	L	1.275	61.559	0.328	0.191	-0.137
306	146.361	L	2.444	62.309	0.326	0.184	-0.142
311	146.361	L	2.891	63.060	0.324	0.185	-0.139
316	**146.361**	**L**	**3**	**63.810**	**0.324**	**0.189**	**-0.135**

The highest values (0.522 – 0.552) are calculated on the circulating carriageway, at approx. CH 256 – CH 266. This location is in between the last two speed survey sites, where the vehicles accelerate from approximately 53km/h as they circulate, to approximately 63km/h as they exit the roundabout. As mentioned previously, the speeds have been linearly interpolated in between speed survey sites. As it is not known exactly where the vehicles begin to accelerate, the assumed speeds that are generating these high values of side friction may not actually be occurring, and can be given less consideration than those at other areas where the confidence in the interpolated speeds is higher.

Elsewhere on RB1, the calculated side friction factors are generally below the Austroads (2015a) maximum recommended values, or they are generally equal to or less than the value of f = 0.5, as found by Maycock and Hall (1984) to be the maximum recorded value at roundabouts.

Table 29 shows that the ANRDT software is using a maximum value of f = 0.5 to predict vehicle speeds.

Comparison of the actual recorded speeds and calculated side friction factors versus the predicted ARNDT values shows that, with the exception of the exit curve (which is non-critical element in this instance) the actual recorded speeds at RB1 are equal to or less than the ARNDT predicted speeds, and the actual calculated values of side friction are generally at or below the values used by ARNDT to predict the vehicle speeds.

Table 29 – Actual vs ARNDT predicted speed and side friction values at RB1

Curve	Speed (km/h)		calculated f	
	ARNDT	Actual	ARNDT	Actual
1	83.391	79.236	0.185	0.209
2	74.637	65.584	0.364	0.292
3 (Entry)	61.951	56.196	0.493	0.415
4 (Circulating)	53.116	53.305	0.501	0.492
5 (Exit)	53.116	63.810	0.170	0.189

4.2.4 RB1 - Medium and Heavy Vehicle (Classes 3 – 12) Side Friction Values

As shown in Section 3.3.3, and Table 8, the Medium and Heavy Vehicle category travels through RB1 at an average speed of 2.39km/h less than the All Vehicles category at any given element. Therefore, as shown below in Table 30, the calculated side friction values are slightly lower than those calculated for the All Vehicles category.

Table 30 – Calculated coefficients of side friction for Medium and Heavy Vehicles (Classes 3 – 12)

Medium & Heavy Vehicles (Classes 3 - 12)							
Chainage	Actual Travelled Radius	Curve Direction	Xfall	85 % Speed	Abs Max f	calc 85 % f	f difference
36	**207.26**	**L**	**3**	**76.849**	**0.212**	**0.194**	**-0.018**
41	207.26	L	3.000	75.798	0.215	0.188	-0.027
46	207.26	L	2.567	74.748	0.218	0.187	-0.031
51	207.26	L	1.967	73.698	0.221	0.187	-0.034
56			1.367	72.648	0.224		
61			0.767	71.598	0.227		
66			0.167	70.548	0.230		
71			-0.433	69.497	0.231		
76			-1.033	68.447	0.232		
81	105.2	R	-1.633	67.397	0.233	0.324	0.091
86	105.2	R	-2.233	66.347	0.234	0.307	0.073
91	105.2	R	-2.833	65.297	0.235	0.291	0.056
96	105.2	R	-3.000	64.247	0.236	0.279	0.043
101	**105.2**	**R**	**-3**	**63.197**	**0.237**	0.269	**0.032**
106	105.2	R	-3.000	62.644	0.238	0.264	0.026
111	105.2	R	-2.587	62.092	0.238	0.263	0.025
116	105.2	R	-1.987	61.540	0.239	0.264	0.025
121			-1.387	60.988	0.240		
126			-0.787	60.435	0.240		
131			-0.187	59.883	0.241		
136	103.83	L	0.413	59.331	0.241	0.263	0.022
141	103.83	L	0.953	58.779	0.242	0.252	0.010
146	103.83	L	1.619	58.226	0.242	0.241	-0.001
151	58.4	L	2.185	57.674	0.243	0.427	0.184
156	58.4	L	2.770	57.122	0.243	0.412	0.169
161	58.4	L	3.005	56.570	0.244	0.401	0.157
166	58.4	L	2.999	56.017	0.244	0.393	0.149
171	57	L	3.004	55.465	0.245	0.395	0.150
176	57	L	2.997	54.913	0.246	0.387	0.141
181	57	L	2.729	54.361	0.246	0.381	0.135
186	**57**	**L**	**2.173**	**53.809**	**0.247**	0.378	**0.131**
191	57	L	1.419	53.568	0.247	0.382	0.135
196	57	L	0.738	53.327	0.247	0.385	0.138
201	57	L	-0.336	53.086	0.247	0.393	0.146
206			-3.008	52.845	0.248		
211	78.7	R	-3.085	52.604	0.248	0.246	-0.002
216	78.7	R	-3.036	52.363	0.248	0.244	-0.004
221	78.7	R	-2.984	52.122	0.248	0.242	-0.006
226	42.89	R	-2.997	51.881	0.249	0.464	0.215
231	42.89	R	-2.985	51.640	0.249	0.460	0.211
236	42.89	R	-2.979	51.399	0.249	0.455	0.206
241	42.89	R	-2.983	51.158	0.249	0.451	0.202
246	**42.89**	**R**	**-3**	**50.918**	**0.250**	0.446	**0.196**
251	42.89	R	-2.987	51.668	0.249	0.460	0.211
256	42.89	R	-2.979	52.418	0.248	0.475	0.227
261	42.89	R	-2.983	53.169	0.247	0.489	0.242
266	42.89	R	-3.005	53.919	0.247	0.504	0.257
271	150.826	R	-2.996	54.669	0.246	0.126	-0.120
276			-2.985	55.420	0.245		
281	500	L	-2.866	56.170	0.244	0.078	-0.166
286	500	L	-2.698	56.920	0.244	0.078	-0.166
291	146.361	L	-2.012	57.671	0.243	0.199	-0.044
296	146.361	L	0.841	58.421	0.242	0.175	-0.067
301	146.361	L	1.275	59.171	0.241	0.176	-0.065
306	146.361	L	2.444	59.922	0.241	0.169	-0.072
311	146.361	L	2.891	60.672	0.240	0.169	-0.071
316	**146.361**	**L**	**3**	**61.423**	**0.239**	**0.173**	**-0.066**

However, as per Austroads (2015a), the maximum recommended values of side friction for this vehicle category are considerably lower than the All Vehicles category, and as such, a much larger discrepancy between the calculated and recommended side friction factors exists at RB1 for this vehicle category.

4.2.5 RB1 - Heavy Vehicle (Classes 6 – 12) Side Friction Values

It is this vehicle category that comes under the most scrutiny in this case study, as it is this vehicle category that has been identified as having a history of issues at RB1.

As shown in Section 3.3.3, and Table 6, the Heavy Vehicle category travels through RB1 at an average speed of 8.68km/h less than the All Vehicles category.

As such, and as shown below in Table 31, considerably lower values of side friction are calculated for this category. However, due to the lower recommended absolute maximum values of side friction as per Austroads (2015a), a significant discrepancy still exists between the recommended and calculated values, and a significant length of the RB1 approach geometry (CH 151 to CH 266) is above the absolute maximum recommended value of f = 0.25.

Table 31 – Calculated coefficients of side friction for Articulated Heavy Vehicles (Classes 6 – 12)

Heavy Vehicles (Classes 6 - 12)							
Chainage	Actual Travelled Radius	Curve Direction	Xfall	85 % Speed	Abs Max f	calc 85 % f	f difference
36	**207.26**	**L**	**3**	**70.556**	**0.230**	**0.159**	**-0.071**
41	207.26	L	3.000	69.121	0.231	0.152	-0.079
46	207.26	L	2.567	67.686	0.233	0.148	-0.085
51	207.26	L	1.967	66.252	0.234	0.147	-0.087
56			1.367	64.817	0.236		
61			0.767	63.382	0.237		
66			0.167	61.947	0.239		
71			-0.433	60.513	0.240		
76			-1.033	59.078	0.241		
81	105.2	R	-1.633	57.643	0.243	0.232	-0.011
86	105.2	R	-2.233	56.208	0.244	0.214	-0.030
91	105.2	R	-2.833	54.774	0.246	0.196	-0.050
96	105.2	R	-3.000	53.339	0.247	0.183	-0.064
101	**105.2**	**R**	**-3**	**51.904**	**0.249**	**0.172**	**-0.077**
106	105.2	R	-3.000	51.646	0.249	0.170	-0.079
111	105.2	R	-2.587	51.388	0.249	0.172	-0.077
116	105.2	R	-1.987	51.130	0.249	0.176	-0.073
121			-1.387	50.872	0.250		
126			-0.787	50.613	0.250		
131			-0.187	50.355	0.250		
136	103.83	L	0.413	50.097	0.250	0.186	-0.064
141	103.83	L	0.953	49.839	0.250	0.179	-0.071
146	103.83	L	1.619	49.581	0.250	0.170	-0.080
151	58.4	L	2.185	49.323	0.250	0.306	0.056
156	58.4	L	2.770	49.065	0.250	0.297	0.047
161	58.4	L	3.005	48.807	0.250	0.291	0.041
166	58.4	L	2.999	48.548	0.250	0.288	0.038
171	57	L	3.004	48.290	0.250	0.292	0.042
176	57	L	2.997	48.032	0.250	0.289	0.039
181	57	L	2.729	47.774	0.250	0.288	0.038
186	**57**	**L**	**2.173**	**47.516**	**0.250**	0.290	**0.040**
191	57	L	1.419	47.416	0.250	0.296	0.046
196	57	L	0.738	47.317	0.250	0.302	0.052
201	57	L	-0.336	47.217	0.250	0.311	0.061
206			-3.008	47.117	0.250		
211	78.7	R	-3.085	47.018	0.250	0.190	-0.060
216	78.7	R	-3.036	46.918	0.250	0.190	-0.060
221	78.7	R	-2.984	46.818	0.250	0.189	-0.061
226	42.89	R	-2.997	46.719	0.250	0.371	0.121
231	42.89	R	-2.985	46.619	0.250	0.369	0.119
236	42.89	R	-2.979	46.519	0.250	0.367	0.117
241	42.89	R	-2.983	46.420	0.250	0.366	0.116
246	**42.89**	**R**	**-3**	**46.320**	**0.250**	0.364	**0.114**
251	42.89	R	-2.987	46.981	0.250	0.375	0.125
256	42.89	R	-2.979	47.641	0.250	0.387	0.137
261	42.89	R	-2.983	48.302	0.250	0.398	0.148
266	42.89	R	-3.005	48.963	0.250	0.410	0.160
271	150.826	R	-2.996	49.624	0.250	0.099	-0.151
276			-2.985	50.284	0.250		
281	500	L	-2.866	50.945	0.250	0.070	-0.180
286	500	L	-2.698	51.606	0.249	0.069	-0.180
291	146.361	L	-2.012	52.266	0.248	0.167	-0.081
296	146.361	L	0.841	52.927	0.248	0.142	-0.106
301	146.361	L	1.275	53.588	0.247	0.142	-0.105
306	146.361	L	2.444	54.249	0.246	0.134	-0.112
311	146.361	L	2.891	54.909	0.246	0.133	-0.113
316	**146.361**	**L**	**3**	**55.570**	**0.245**	**0.136**	**-0.109**

As shown in Section 2.9.3, several studies have shown that heavy vehicles may become unstable and roll at side friction values of f = 0.25 and up.

Therefore, further analysis of the speeds travelled by this vehicle category is required, to determine why such high coefficients of side friction are being generated. This analysis is described in the following sections.

4.2.6 RB1 – Rate of Rotation Analysis

Before the heavy vehicle speeds were analysed further, the crossfall rates of rotation being experienced by drivers at the surveyed 85th percentile speeds was analysed.

As mentioned in Section 2.2.3, and as per Austroads (2016), the maximum rate of crossfall rotation for this speed environment (< 80km/h) is 3.5% per second.

The crossfalls travelled by the heavy vehicles have been determined as previously described using AutoTURN and 12D design software. The crossfall transitions have been entered into Excel, and using the average heavy vehicle 85th percentile speeds (measured over the length of each transition) the rates of rotation have been calculated.

The superelevation diagram, and rates of rotation can be viewed diagrammatically below in Figure 50, and calculations and results are summarised in Table 32 below:

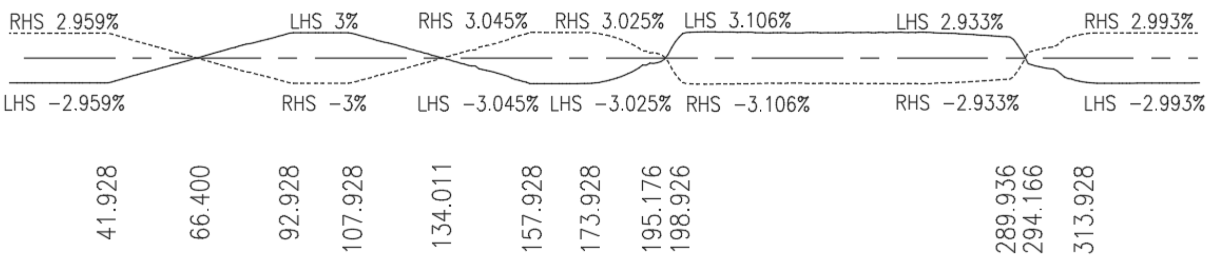


Figure 50 – RB1 – Superelevation Diagram

Table 32 – RB1 – Heavy Vehicle (Classes 6 – 12) rates of rotation calculations

Heavy Vehicle (Classes 6 - 12) Rates of crossfall rotation								
Xfall		e2 - e1	Chainage	Transition Length (m)	Average 85th % speed over transition length (km/h)	Average 85th % speed (m/s)	Travel Time (seconds)	Rate of Rotation (%/s)
e2	2.959	5.959	41.928	50.9	62	17.222	2.955	2.016
e1	-3		92.828					
e2	-3	6.045	107.928	50	50.3	13.972	3.579	1.689
e1	3.045		157.928					
e2	3.025	3.025	173.928	21.248	47.5	13.194	1.610	1.878
e1	0		195.176					
e2	-3.106	3.106	198.926	3.75	47.3	13.139	0.285	10.883
e1	-2.933	2.933	289.936	4.23	52.3	14.528	0.291	10.073
e2	0		294.166					
e1	2.993	2.933	313.928	19.762	54.3	15.083	1.310	2.239

As shown, the crossfall rotates very quickly between CH 195.176 to 198.926, and CH 289.936 to 294.166, distances of only 3.75m and 4.23m respectively, which results in very high rates of rotation being experienced by the heavy vehicles (10.883 % / second), a value more than 3 times the maximum recommended value.

The very high rates of rotation occur at the transitions of the entry and exit curves with the circulating carriageway. This occurs because the entry and exit curves are left-hand curves with crossfall falling to the left, and the circulating carriageway is a right-hand curve with crossfall falling to the right, and unlike the preceding reverse curves, insufficient length of straight has been provided, to allow for gradual transition of crossfall between the curves.

The abrupt changes in crossfall can be seen by reviewing the as-constructed surface contours shown below in Figure 51:

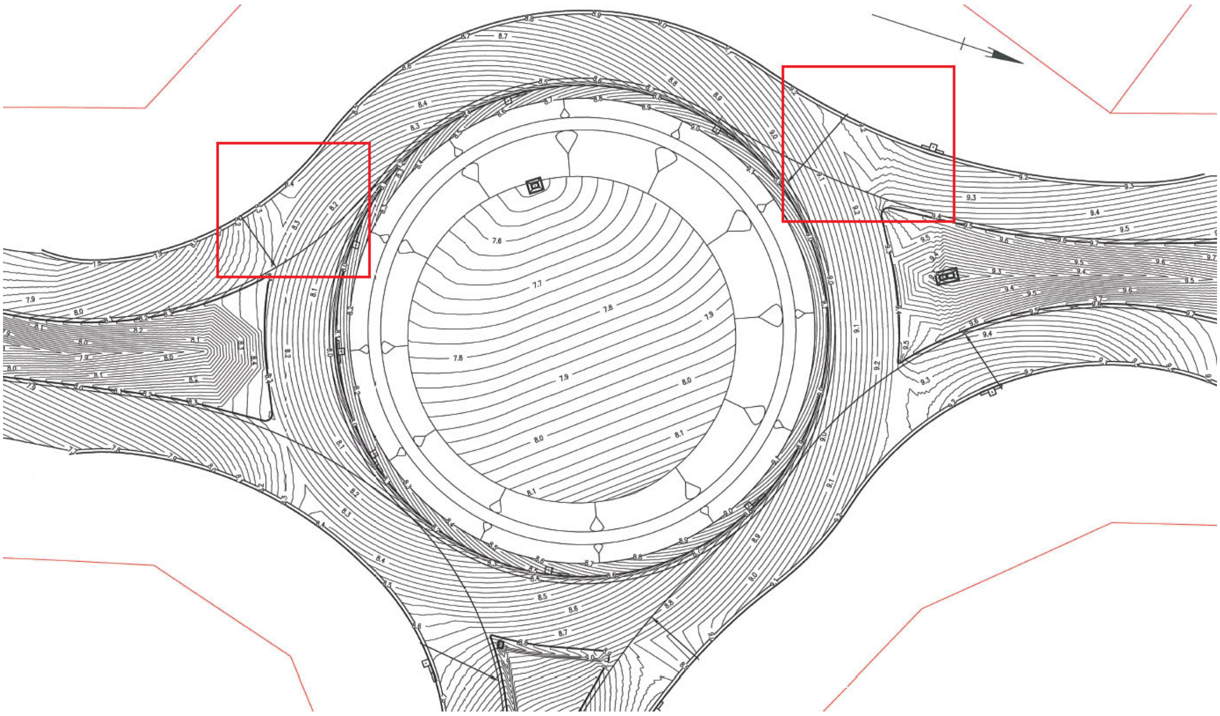


Figure 51 – RB1 – As-constructed surface contours showing crossfall transitions

4.2.7 RB1 - Adverse Crossfall considerations

The above analysis has also highlighted an additional issue concerning crossfall rotation and heavy vehicle stability.

The lack of straight between the entry curve and circulating carriageway results in the end of the entry curve containing crossfall in the wrong direction, ie adverse crossfall.

As shown below in Figure 52, the last approximately 3.7m of the Radius 57m left hand curve contains full 3% super in the wrong direction, ie to the outside of the curve:

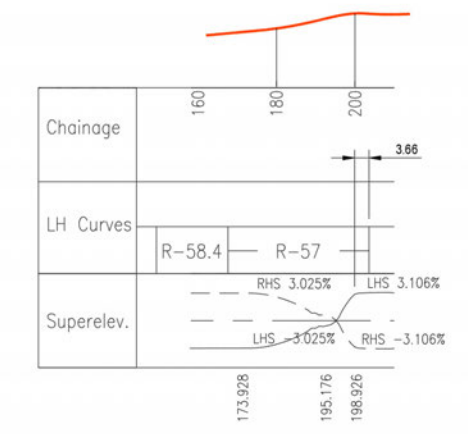


Figure 52 – RB1 – Enlarged view of superelevation diagram

As per Austroads (2016), adverse crossfall may cause problems for trucks, and should be avoided where practicable. The reason that it may cause problems is because as per Austroads (2016) Appendix H, Section H.2.3, adverse superelevation reduces the horizontal distance between the centre of gravity and the overturning hinge point. The relationship between the centre of gravity and the overturning hinge point are shown below in Figure 53:

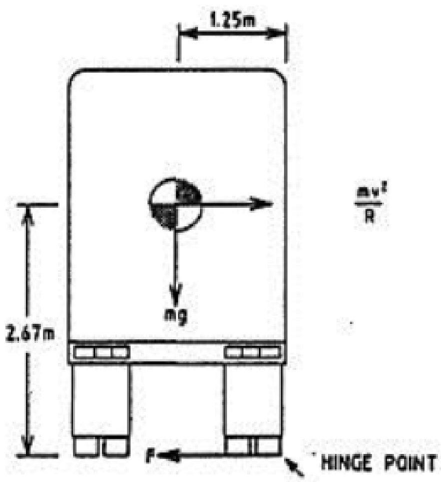


Figure 53 – Overturning moment on a turning truck

Source: Austroads (2016) Figure H4

4.2.8 RB1 – Vehicle Speeds

As shown in Section 4.2.2, vehicle speeds and calculated coefficients of side friction are generally in line with recommended values for light vehicles, and it can therefore initially be assumed that the RB1 geometry is sound, considering light vehicles only.

When considering how and why the heavy vehicles are generating coefficients of side friction much higher than their recommended values, as compared to light vehicles, modification of RB1's geometry, eg increasing curve radii and central island diameter to better suit heavy vehicles, could be considered, however, this could potentially result in light vehicle speeds significantly higher than those recommended by ARNDT and Austroads (2015a), resulting in an unsafe roundabout for the majority of vehicles.

Putting aside geometry modifications for the moment, the only other variable in the side friction equation is the speed at which the vehicles travel at.

4.2.9 RB1 - Operating Speed and Driver Behaviour Considerations

As mentioned in Section 2.9.1, the reverse curves at high-speed roundabout approaches, and their use as a speed reduction treatment, relies on the concept of the Operating Speed Model, the associated Limiting Curve Speed theories, and driver behaviour to function as intended.

Essentially, the high coefficients of side friction being generated at RB1 are a result of heavy vehicle drivers "overdriving" the curves.

As per Austroads (2016) Section 3.6.1, a typical driver travelling on a long straight followed by a curve, will travel at the desired speed until within approximately 75m of the curve. The driver will then decelerate to a speed that is considered safe for the curve ahead. Car drivers are likely to enter the curve at a speed that is high for the curve, and continue to decelerate within the curve, commonly within the first 80m. Truck drivers will generally decelerate to what they consider the appropriate speed before the start of the curve, because of the dangers associated with trucks braking on curves.

4.2.10 RB1 - Heavy Vehicle (Classes 6 – 12) Speeds & Deceleration

Review of the Heavy Vehicle speeds at the 5 known speed survey sites reveals the amount of deceleration being performed between curves, shown below in Table 33:

Table 33 – RB1 – Heavy Vehicle (Classes 6 – 12) deceleration/acceleration between curves

Heavy Vehicles (Classes 6 - 12)			
Chainage	Curve	85 % Speed	Deceleration/Acceleration
36	1	70.556	
101	2	51.904	-18.652
186	3 (Entry)	47.516	-3.356
246	4 (Circulating)	46.320	-1.454
316	5 (Exit)	55.570	8.589

If the heavy vehicle drivers were to drive the curves at speeds which resulted in side friction not being greater than absolute maximum recommended values, the required speeds would be lower, and the required amount of deceleration would be higher. These calculations and results are summarised below in Table 34:

Table 34 – RB1 – Heavy Vehicle (Classes 6 – 12) required speeds and deceleration to achieve maximum recommended values of side friction

Heavy Vehicles (Classes 6 - 12)						
Chainage	Curve	85 % Speed	Speed Required	Difference	Abs Max f	Deceleration Required
101	2	51.904	61.054	9.150	0.249	-21.673
186	3 (Entry)	47.516	44.351	-3.165	0.250	-16.702
246	4 (Circulating)	46.320	39.051	-7.269	0.250	-5.300
316	5 (Exit)	55.570	71.496	15.926	0.245	32.445

As per Austroads (2016), the deceleration coefficient required by vehicle standards regulations for single unit trucks, semi-trailers and B-Doubles on dry sealed roads is 0.29.

Given that heavy vehicles require straight lengths of road to carry out their braking (Austroads (2016) Section 3.6.1), determination of the lengths required for this deceleration has been performed, to critically review RB1's geometry, and assess if sufficient length between curves has been provided.

The deceleration equation has been derived by modification of the Stopping Sight Distance (SSD) Equation 1 of Austroads (2016):

$$SSD = \frac{R_T V}{3.6} + \frac{V^2}{254(d + 0.01a)}$$

The modification to the equation involves the removal of the Reaction Time (R_T) component, and rearranging the remainder of the equation to subtract the total deceleration length of Speed 2 (V2) from the total deceleration length of Speed 1 (V1), which gives the resultant deceleration length.

The modified equation is shown below:

$$D = \frac{V1^2}{254(\mathrm{d} + 0.01a)} - \frac{V2^2}{254(\mathrm{d} + 0.01a)}$$

Where:

D = Deceleration Length (m)

V1 = Speed 1 / Start Speed

V2 = Speed 2 / End Speed

d = deceleration coefficient (0.29)

a = longitudinal grade (ignored for simplicity and due to relatively flat grades at RB1)

Table 35 below shows the required deceleration distances for Heavy Vehicles:

Table 35 – RB1 – Heavy Vehicle (Classes 6 – 12) Deceleration Lengths Required

		Heavy Vehicles (Classes 6 - 12)	
Chainage	**Curve**	**Speed Required**	**Deceleration Distance Required**
36	1	82.727	
101	2	61.054	42.305
186	3 (Entry)	44.351	23.900
246	4 (Circulating)	39.051	6.001
316	5 (Exit)	71.496	

Comparison of the required deceleration lengths to the lengths of straights provided on the RB1 northbound approach leg reveals that insufficient distance between the curves has been provided to allow for sufficient deceleration, as summarised below in Table 36:

Table 36 – RB1 – Comparison of required deceleration lengths vs lengths of straights provided (Control Line)

Curve #	Start/End CH	CH (m)	Distance between curves achieved (m)	Distance between curves required for deceleration (m)
Curve 1	End CH	57.404	20.000	42.305
Curve 2	Start CH	77.404		
	End CH	122.573	20.001	23.900
Curve 3 (Entry)	Start CH	142.574		
	End CH	216.837	0.000	6.001
Curve 4 (Circulating)	Start CH	216.837		
	End CH	275.910	0.000	0.000
Curve 5 (Exit)	Start CH	275.910		

Note: The curve start and end chainages documented above represent the control line of the RB1 approach geometry only, and do not represent the actual travelled path.

The actual travelled path by the cab of the heavy vehicle is shown below in Figure 54:

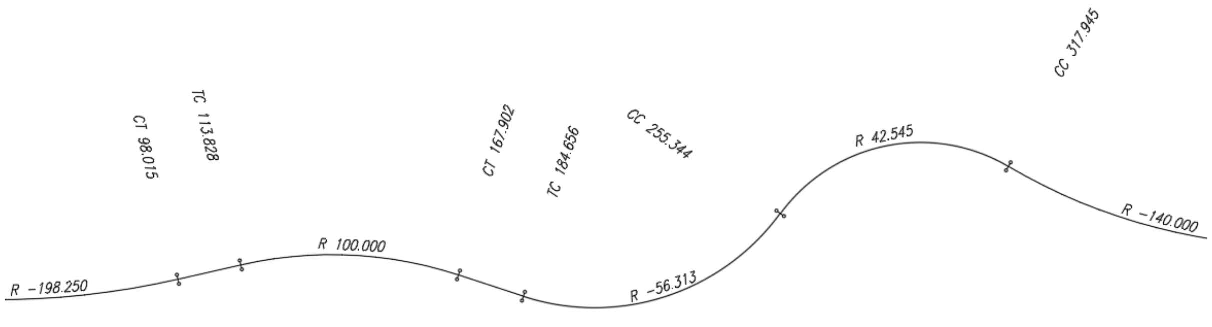


Figure 54 – RB1 – Actual travelled cab path

Comparison of the required deceleration lengths to the lengths of straights provided on the actual travelled path of the heavy vehicle cab on RB1 northbound approach leg reveals that insufficient distance between the curves has been provided to allow for sufficient deceleration, as summarised below in Table 37:

Table 37 – RB1 – Comparison of required deceleration lengths vs lengths of straights provided (Actual cab travelled path)

Curve #	Start/End CH	CH (m)	Distance between curves achieved (m)	Distance between curves required for deceleration (m)
Curve 1	End CH	98.015	15.813	42.305
Curve 2	Start CH	113.828		
	End CH	167.902	16.754	23.900
Curve 3 (Entry)	Start CH	184.656		
	End CH	255.344	0.000	6.001
Curve 4 (Circulating)	Start CH	255.344		
	End CH	317.945	0.000	0.000
Curve 5 (Exit)	Start CH	317.945		

In any case, the requirement for length of straight between reverse curves is set by Austroads (2016), Section 7.5.3, which states that when providing for trucks, reverse curves should be joined by a tangent at least 0.7V m long to allow for the tracking of these large vehicles. Where deceleration is required on the approaches to a lower radius curve, sufficient distance must be provided to enable the drivers to react and decelerate.

Using the average 85th percentile speeds in between the curves, the lengths of straights based on the 0.7V requirement are as per Table 38 below:

Table 38 – RB1 – Distance required between curves based on 0.7V

Curve #	Average Speed (required) Between Curves (km/h)	Distance between curves based on 0.7V (m)
Curve 1		
	71.890	50.323
Curve 2		
	52.703	36.892
Curve 3 (Entry)		
	41.701	29.191
Curve 4 (Circulating)		
	55.274	38.692
Curve 5 (Exit)		

4.3 RB2 – Results & Discussion

The 2019 speed survey was analysed using the MetroCount software, and reports were generated on both All Vehicles (Classes 1 – 12) and Heavy Vehicles (Classes 6 – 12).

A comparison of the measured speeds in 2015 and 2019 is shown below in Table 39:

Table 39 – RB2 85th percentile speeds before and after supplementary sign installation

RB2 - 85th percentile speeds (km/h)				
Year	All Vehicles (Classes 1 - 12)		Heavy Vehicles (Classes 6 - 12)	
	Northbound	Southbound	Northbound	Southbound
2015	51.57	47.79	43.53	41.76
2019	47.97	48.24	40.77	44.91
Difference	-3.6	0.45	-2.76	3.15

As shown in the table above, the speeds in the northbound direction have decreased between 2.7 to 3.6 km/h, however in the southbound direction, the speeds appear to have increased anywhere from 0.45 to 3.15 km/h.

The increased speeds in the southbound direction are disconcerting because there is strong sentiment within the Road Authority that the revised and added signage has definitely reduced the heavy vehicle roll over crashes, which is also evident in the approx. 4 years of crash history following the signage review.

There are potentially several factors that could be skewing the southbound direction speed survey results:

- At the time of the 2019 speed survey, roadworks in the area were present, including the closure of the western (ie to the right of the southbound leg) side road. This means that the only circulating traffic encountered by southbound approaching vehicles was those doing a u-turn from the northbound direction, ie very little. Therefore, with little to no traffic on their right to give way to, the southbound vehicles could be entering the roundabout at higher speeds than if the side road was operational.
- There is some doubt as to whether the 2019 speed survey was conducted in the exact same location as the 2015 data, which could be affecting the speeds significantly.

Chapter 5 – Conclusions & Recommendations

5.1 Summary of analysis and critical review of current standards

The current standards do not adequately provide for heavy vehicle usage of roundabouts, and in particular, high speed approaches.

The current curve radii associated with central island radii, circulating carriageway widths, approach reverse-curve geometry, and maximum entry path radii are too small for heavy vehicles. This requires the heavy vehicles to perform one of two undesirable actions:

1. Decelerate significantly more than light vehicles, and at rates outside the maximum recommended by Austroads (2015a) and ARNDT to minimise accidents at roundabout.
2. Overdrive the curves at speeds that generate side friction factors above the heavy vehicle rollover threshold.

Additionally, the current standards do not provide explicit or clear guidance to designers regarding sufficient allowance for separating tangents between curves, which are essential to facilitate adequate heavy vehicle deceleration between curves.

Finally, the current signage standards do not adequately consider the additional requirements of heavy vehicles at high-speed roundabout approaches. In particular, there is a need to warn heavy vehicle drivers that the intended speed-reduction mechanism most usually employed, ie reverse curves, can actually be a hazard to heavy vehicle drivers, and they need to reduce their speed accordingly.

5.2 Summary of RB1 geometry analysis

The geometry of RB1 is generally in accordance with the relevant Austroads standards, and performs reasonably well for the light vehicle category, as evidenced by the above findings, and lack of crash history associated with this vehicle category.

For the articulated heavy vehicle category however, the following conclusions can be made:

- Very high coefficients of side friction are being generated, partly contributing to heavy vehicle instability, and in some cases, roll over crashes
- The high coefficients of side friction are a result of excessive speeds by the vehicle category
- The excessive speeds are a result of insufficient advanced warning to drivers (ie via signage) to reduce their speeds, and insufficient length of straights provided between curves to allow for heavy vehicle deceleration
- The lack of straights provided between the entry, circulating, and exit curves also results in:

    - Very high rates of crossfall rotation, contributing to heavy vehicle instability
    - A portion of the entry and exit curves containing adverse crossfall, contributing to heavy vehicle instability

- At the end of the entry curve, and the start of the exit curve, the above issues coincide. At the entry curve in particular, ie CH 201:
    - Coefficient of side friction = 0.311
    - Truck is turning left with crossfall to the right (adverse crossfall)
    - The crossfall has just finished rotating up at a rate (10.88 % / second) more than 3 times the maximum recommended value

5.2.1 Summary of RB2 Signage and Speed Review

Despite the inconclusive speed survey results, the strong sentiment within the Road Authority regarding the effectiveness of the amended signage, and the lack of crash history since, is compelling enough to consider the revised signage as effective and warranted. Further work is required to confirm the speed surveys, and document the assumed effectiveness of the signage.

5.3 Recommendations

5.3.1 Recommended Supplementary Standards

It is recommended that the current Austroads (2015a) Roundabout standards are supplemented with a specific heavy vehicle guideline, based on the learnings of this dissertation, and drawing on proven and documented learnings from other geometric guidelines, including Austroads (2016), DTMR-QLD (2016), and MRWA (2019).

A draft supplement has been produced as part of this dissertation, attached as Appendix H.

The draft supplement is produced in the same format as Austroads (2015a), and focuses on critical elements such as:

- Central Island Geometry
- Approach and Entry Geometry
- Circulating Carriageway Geometry
- Heavy Vehicle Limiting Curve Speed and the additional considerations required for this vehicle category at roundabouts
- Heavy Vehicle rollover thresholds and how to avoid them
- Special signage considerations for heavy vehicles at roundabouts

The draft supplement includes examples of preferred combinations of geometry and signage to achieve the recommended outcomes.

5.3.2 RB1 Interim Recommendations

As an interim measure, it is recommended that the signage at RB1 be revised in line with the amended RB2 signage, and the recommended signage treatments as per Appendix G.

This will provide further warning to heavy vehicle drivers that they need to reduce their speed, which in turn will lower the coefficients of side friction being generated and reduce the crossfall rate of rotation, which will result in fewer heavy vehicle roll over crashes.

5.3.3 RB1 Ultimate Recommendations

Significant modification and/or upgrade of the RB1 approach geometry may be impractical and out of scope for the Road Authority, however if such upgrades were to be considered, the following recommendations are made, in addition to the above signage recommendations:

- Reconstruction of the northbound and southbound approaches, involving retention of the current curve radii, with horizontal straights added between each curve (including exit curves) at lengths of 0.7V, as per Table 38. The added and increased lengths of straights will more effectively allow for the tracking of the large heavy vehicles, and give them more time to react and decelerate, in line with Austroads (2016) Section 7.5.3. This will help to lower the heavy vehicle speeds, which in turn will result in lower coefficients of side friction being generated.
- The recommended addition of the horizontal straights between the entry, circulating, and exit curves will also allow for the correct superelevation transitions to be applied, in line with Austroads (2016) Section 7.7. This will rectify the issues associated with the very high rates of crossfall rotation.

Chapter 6 - Limitations and Recommended Further Work

Limitations associated with accuracy of the speed survey data at RB1 Are described in detail in Section 3.3.3.

In addition to refining and confirming the speed survey results, recommended further work, outside the scope of this dissertation, is summarised below:

- Additional case-studies
  - This dissertation has analysed the geometry and performance of only one existing roundabout in detail, whereas papers such as Arndt (1998) analysed over 100 roundabouts over a period of more than 10 years.
  - Geometric analysis of an existing high-speed roundabout that is perceived to be successfully trafficked by a large percentage of heavy vehicles is also recommended
- Review of the developed recommended treatments by a road standard authority such as Austroads or TMR's Engineering & Technology branch
- Trial of recommendations; for example, build a roundabout using the recommended treatments and monitor and evaluate its performance
- Survey of relevant heavy vehicle experts including drivers, in an effort to evaluate the recommendations, and confirm driver behaviour assumptions

Chapter 7 – References

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Appendix A – Project Specification

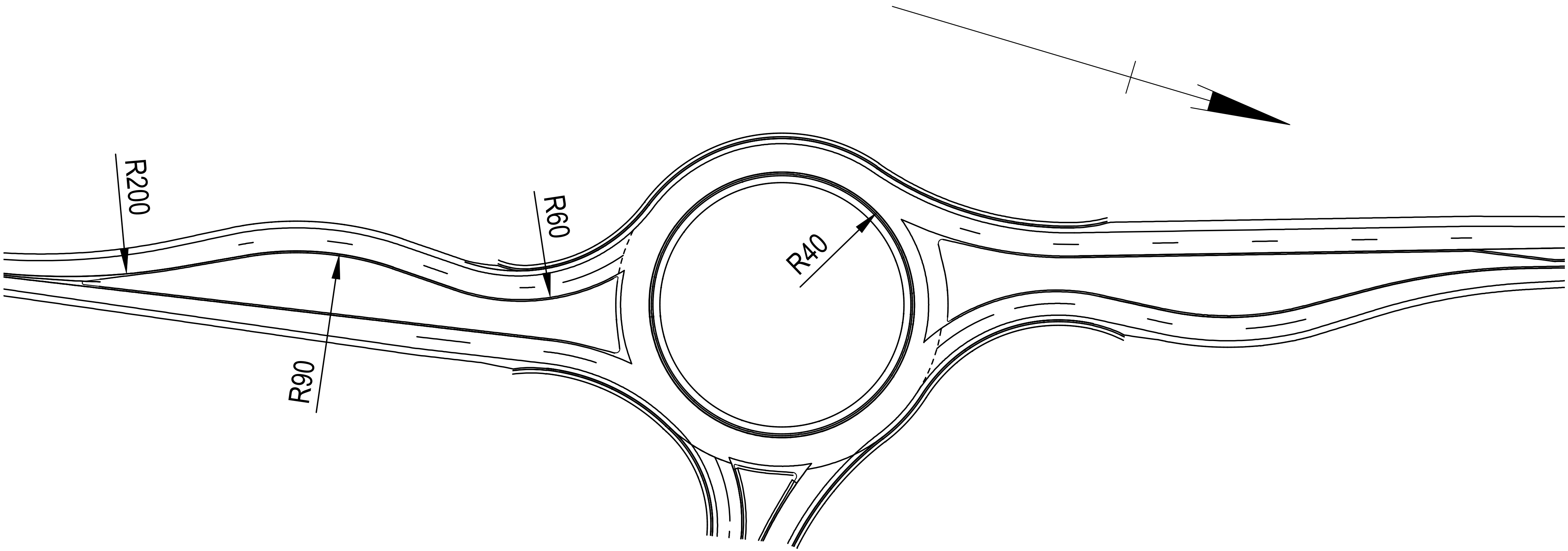
ENG4111/4112 Research Project

Project Specification

For:	Mark Tomarchio, USQ Student # [redacted]
Title:	Improved theory for design of high speed roundabouts to suit heavy vehicles
Major:	Civil Engineering
Supervisors:	Dr Soma Somasundaraswaran (USQ)
Enrolment:	ENG4111 – EXT S1. 2019 and ENG4112 – EXT S2, 2019
Project Aim:	To develop additional guidance on the correct way to design roundabouts to suit high speed approaches, for use by heavy vehicles
Programme:	*Version 1 – 20/03/19*

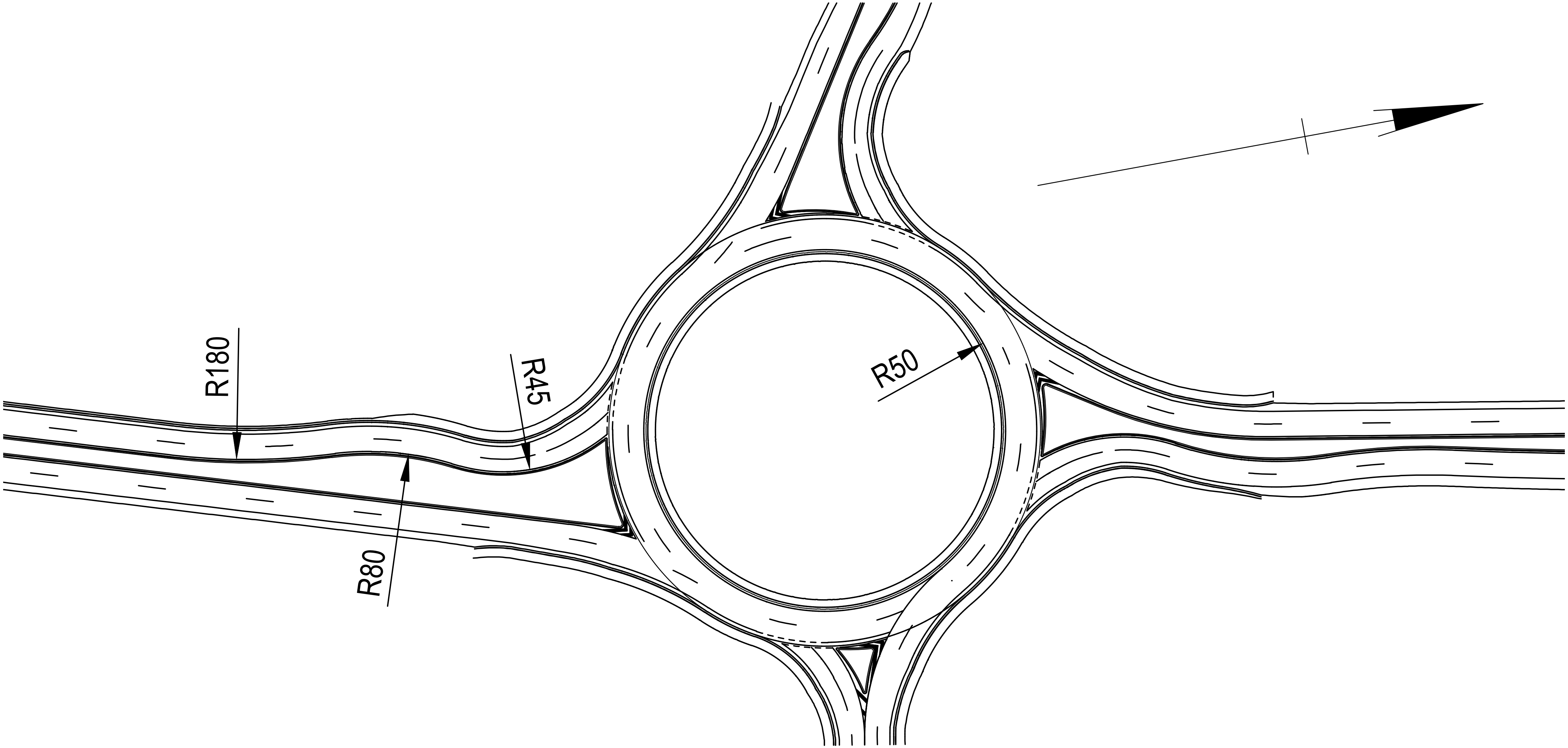
1. Phase 1 – Project Creation, Proposal & Specification
    a. Discuss project origin and perceived problems with potential sponsors and supervisors
    b. Draft Project Proposal
    c. Develop Project Specification
2. Phase 2 – Research investigation and data collection (sue to the nature of the testing, some of the tasks in this phase will run concurrently with Phase 3)
    a. Literature Review
    b. Identify other similar roundabouts for comparison
    c. Crash History Investigation
    d. Approach speed surveys
    e. Ballbank testing
    f. ARRB Dynamic Stability Testing
    g. Interview drivers
3. Phase 3 – Analysis and Testing (some of the tasks in Phase 3 will be preliminary until Phase 2 testing is finalised)
    a. Review data and identify gaps
    b. Desktop design reviews of roundabouts
    c. Analyse Approach Geometry
    d. Analyse rate of rotation
4. Phase 4 – Advanced Analysis, Problem Identification, and Design
    a. Identify root causes of the issues
    b. Finalise testing and analysis
    c. Develop designs to rectify issues
    d. Develop guideline addendum document
5. Phase 5 – Peer Review and Dissertation Finalisation

Appendix B – RB1 – Working Plan



APPENDIX B – RB1 – PLAN VIEW

Appendix C – RB2 – Working Plan



APPENDIX C – RB2 – PLAN VIEW

Appendix D – MRWA (2019a), Drawing No. 200331-199-4

Appendix E – MRWA (2019a), Drawing No. 200331-0203-7

Appendix F – RB1 & RB2 Crash History Summaries

Appendix F - RB1 & RB2 Crash History Summaries

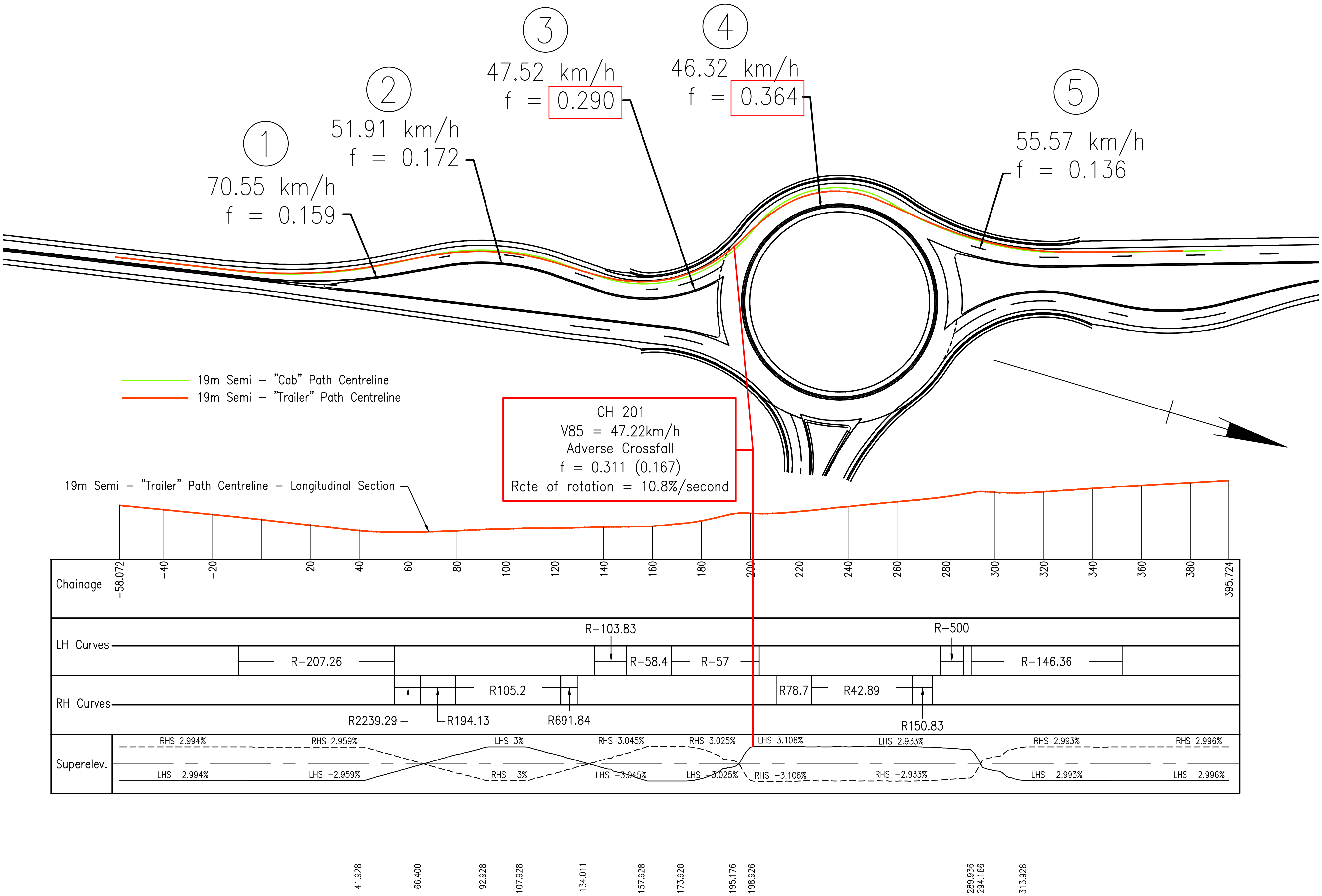
RB1 - Crash History Summary

Date	Travel Direction	Entering/Exiting	Side Rolled onto	Location Relative to Roundabout	Severity	Violation	Notes
Aug 2016	South	Entering	Left	Entering on northern side	Unknown	Unknown	All details derived from media report
Sep 2018	North	Entering	Right	Facing north on the southern side	Received Medical Treatment	Driving without due care and attention	
Sep 2018	South	Exiting	Left	Exiting the roundabout	Received Medical Treatment	Driving without due care and attention	

RB2 - Crash History Summary

Date	Travel Direction	Entering/Exiting	Side Rolled onto	Location Relative to Roundabout	Severity	Violation	Notes
Apr 2015	North	Exiting	Right (assumed)	Exiting on northern side	Admitted to hospital	-	B-Double - Crash report mentions "load shift"
Aug 2015	South	Entering	Right	Entering on northern side	Received Medical Treatment	-	

Appendix G – RB1 Geometry Review Plan and Long Section



APPENDIX G – RB1 – GEOMETRY REVIEW PLAN AND LONG SECTION

Appendix H – Supplement to Austroads Part 4B

1. Introduction

1.4 Purpose

The purpose of this supplement is to provide additional and tailored guidance to designers regarding the design of roundabouts to suit heavy vehicles, in particular, high-speed roundabouts. In most situations, the currently used standards are sufficient for the design of low-speed roundabouts to suit light vehicles with occasional heavy vehicle use. Where higher speeds, and/or significant heavy vehicle, or high-centre-gravity heavy vehicle use is expected, designers are encouraged to consider the additional guidance provided in this document.

In some instances, the specific heavy vehicle recommendations in this document may affect a roundabout's performance for use by light vehicles. Engineering judgement is required to determine if the benefits of improving heavy vehicle performance outweighs the costs, and if this is not achievable, alternative designs, and/or potentially alternative intersection types may be required.

For further guidance regarding assessment of warrants for specific heavy vehicle design, refer to Austroads document AP-R211: "Geometric Design For Trucks – When, Where, and How?".

2. Design Principles and Procedure

Accepted without amendment

3. Sight Distance

Accepted without amendment

4. Geometric Design

4.4 Central Island

4.4.3 Central Island Radius

Additions:

The combinations of approach speeds, entering speeds, and central island radii as listed in Table 4.1 rely on vehicles using coefficients of side friction significantly higher than the capabilities of heavy vehicles.

As per Austroads (2016) Table 7.5, and Austroads (2017) Appendix B, the least stable heavy vehicles will become unstable and roll at coefficients of side friction f = 0.25 to f = 0.35.

Furthermore, the effect of crossfall on the rollover threshold of a heavy vehicle is much prominent than that of a light vehicle. For example, if a circulating carriageway features adverse crossfall (as is commonly provided), a significantly larger central island radius is required than if the circulating carriageway featured superelevation.

Therefore, a maximum side friction factor of f = 0.3 is recommended to be used by designers for determination of central island radii of roundabouts featuring superelevated circulated carriageways.

For circulating carriageways featuring adverse crossfall, it is recommended to reduce the side friction factor to f = 0.2 (ie 2/3 of f = 0.3), in line with Austroads (2016) Table 7.12, and due to the factors that affect truck stability, outlined in Austroads (2017) Appendix B.3.

For determination of heavy vehicle right-turn/circulating speeds, reduced speeds compared to light vehicles can be considered, in line with Austroads (2016) Section 3.7 and Table 3.5.

Table 4.1S provides a guide for the selection of the central island radius and circulating carriageway width for a circular roundabout, to suit 19m Semi-trailer design vehicle.

Table 4.1S:

Circulating Carriageway Type	Desired driver speed on the fastest leg prior to the roundabout (km/h)	Right Turn/Circulating Speed (km/h)	Circulating Carriageway Crossfall (%)	Coefficient of side friction (f)	Min. Right Turn/Circulating Radius (m)	Desirable Central Island Radius (m)	Single Lane Circulating Carriageway Width to Suit 19m Semi (m)
Super	40	15	2	0.3	5.5	10	8
	50	23	2	0.3	13.0	11	7.8
	60	32	2	0.3	25.2	22	6.4
	70	40	2	0.3	39.4	36	5.4
Adverse	40	15	-2	0.2	9.8	10	8
	50	23	-2	0.2	23.1	19	6.6
	60	32	-2	0.2	44.8	42	5.0
	70	40	-2	0.2	70.0	68	4.5

Notes:

1. Desired driver speed on the fastest leg prior to the roundabout = 85th percentile operating speed. Typically sign-post speed limit at 10km/h less.
2. Right Turn/Circulating speeds are based on the desirable 20km/h decrease between the entry curve and a right-turn for cars, plus an additional 5 – 10km/h decrease for trucks. This is based on typical truck driver behaviour and truck capabilities, in line with Part 3 Section 3.7 and Table 3.5. Designers need to consider appropriate speed reduction treatments (eg signage) to convey the message to truck drivers that they need to slow more than cars to negotiate the roundabout. Refer to Section 4.5.2 for the various types of speed reduction treatments.

3. Circulating carriageway crossfall is the recommended 2% adverse scenario. Corresponding coefficient of side friction is therefore 2/3 of the absolute maximum recommended, in line with Part 3 Section 7.8 and Table 7.12, and Part 4B Appendix B, Section B.3.
4. The circulating carriageway coefficients of side friction are based on f = 0.3. Research (eg Ervin et al 1985) shows that the least stable heavy vehicles may roll at f = 0.25. Designers are to consider alternate combinations of speed, radii, crossfalls, and side friction factors, if significant volumes of unstable heavy vehicles are expected to use the roundabout. Refer to Part 4A, Appendix B for further info.
5. 2% crossfalls may require high degree of quality control during construction to ensure positive drainage, and no ponding of water.

To determine central island radius and carriageway width for alternate combinations of speed, crossfall, and design vehicles, designers can refer to the following design process:

Heavy Vehicle Roundabout Geometry Design Process – (Non-reverse curve approach):

1. Determine desired driver speed on fastest leg prior to the roundabout. Typically equal to 85th percentile operating speed.
2. Determine right-turn/circulating speeds, based on desirable 20km/h decrease between the entry curve and a right-turn for cars, plus an additional 5 – 10km/h decrease for trucks, in line with Part 3 Section 3.7 and Table 3.5.
3. Determine appropriate circulating carriageway crossfall. To reduce issues associated with grading superelevation transitions between the entry curve and the circulating carriageway, it is recommended that adverse crossfall on the circulating carriageway is adopted. This requires a coefficient of side friction of 2/3 of the absolute maximum recommended, in line with Part 3 Section 7.8 and Table 7.12, and Part 4B Appendix B, Section B.3. If constrained for space, consider use of superelevated carriageway to reduce central island radius, however designers will need to carefully consider superelevation transition requirements, in line with Part 3 Section 7.7. Maximum rate of rotation to not exceed 3.5% / second.
6. Determine appropriate coefficient of side friction for circulating carriageway. General maximum recommended f = 0.3 for superelevated carriageways, f = 0.2 for adverse crossfall carriageways. Research (eg Ervin et al 1985) shows that the least stable heavy vehicles may roll at f = 0.25. Designers are to consider alternate combinations of speed, radii, crossfalls, and side friction factors, if significant volumes of unstable heavy

vehicles are expected to use the roundabout. Refer to Part 4A, Appendix B for further info.

4. With speed, crossfall, and f known, calculate right-turn/circulating radius.
5. Use vehicle tracking software to determine required central island radius, and circulating carriageway width to suit chosen design vehicle. Allow 0.5m clearance either side of swept path.

4.5 Approach and Entry Geometry

4.5.2 Approach and Entry Treatments

Approach and Entry Treatments

Additions:

As per Austroads (2016) Section 3.6.1, truck drivers will generally decelerate to the appropriate speed for the curve by the start of the curve (unlike car drivers going into the curve) because of the dangers associated with trucks braking on curves.

Therefore, provision of a horizontal straight of length 0.7V between any curve on the approach and departure to a roundabout is required, including the following scenarios;

- Lower speed roundabouts with single entry curve, ie between the entry curve, circulating carriageway, and exit curve
- Higher-speed roundabouts with reverse curve approaches, between all curves including entry/circulating/exit

This is to allow for the tracking of heavy vehicles, and to provide sufficient distance between diminishing reverse curves to enable drivers to react and decelerate, in line with Austroads (2016) Section 7.5.3.

To determine the appropriate speed to use in the calculation of straight required (0.7V) the limiting curve speed of each curve is required to be calculated, and the average speed between curves is to be utilised.

Use of approach reverse curves

Additions:

When providing for heavy vehicles, designers need to carefully consider their vehicle capabilities and driver behaviours compared to light vehicles.

Reverse curve approaches need to be designed in such a way that does not result in heavy vehicles "over-driving" the curves, ie relying on coefficients of side friction that induce instability and result in roll-over crashes.

Appropriately sized curves need to be provided that limit speeds, and sufficient lengths of straights need to be provided between each curve to allow for heavy vehicle tracking and deceleration.

Additionally, it is recommended that all approach curves, and the circulating carriageway be constructed on a single crossfall away from the centre of the road, ie requiring the use of adverse crossfall on some of the approach curves, and on the circulating carriageway. This is to negate the use of superelevation transitions, particularly between the entry curve and the circulating carriageway, which can have a de-stabilising effect on heavy vehicles as they rotate crossfall from one direction to the other. Where adverse crossfall curves are utilised, designers need to restrict the coefficient of side friction to 2/3 the maximum recommended, in line with Austroads (2016) Table 7.12, and due to the factors that affect truck stability, outlined in Austroads (2017) Appendix B.3.

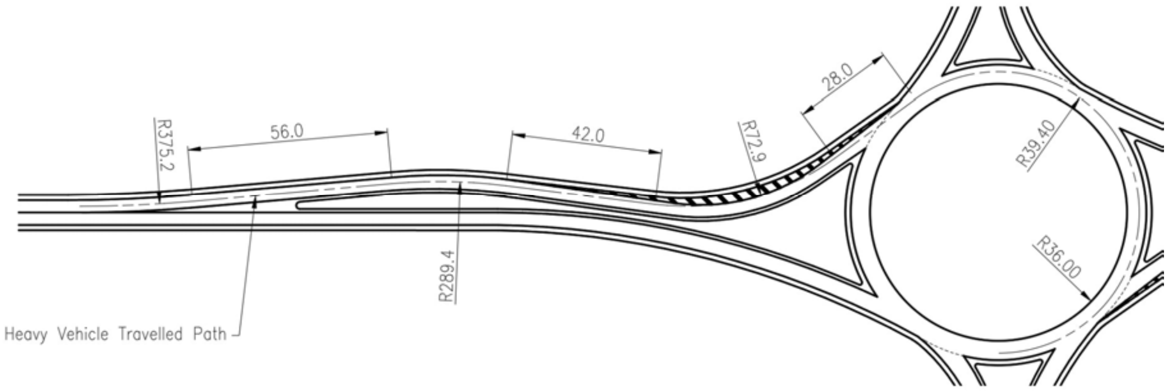
Where space constraints exist, super-elevated curves including the circulating carriageway may be considered, which may allow the use of smaller radii, however designers will need to carefully consider the superelevation transitions in accordance with Austroads (2016) and ensure that maximum rates of rotation are not exceeded.

Table 4.1.1S and Figure 4.4S below show the recommended geometry of an example roundabout approach using reverse curves in a high speed (90km/h design speed/80km/h posted speed) rural environment to suit heavy vehicles:

Table 4.1.1S:

Curve #	Operating Speed (km/h)	Crossfall (%)	f	Travelled Path Radius (m)	Average Speed Between Preceeding Curve - V (km/h)	Length of Straight Required Between Preceeding Curve (0.7V) (m)
Curve 1	90	2	0.150	375.2	-	-
Curve 2	70	-2	0.153	289.4	80.0	56.0
Curve 3 (Entry)	50	2	0.250	72.9	60.0	42.0
Curve 4 (Circulating)	30	-2	0.200	39.4	40.0	28.0

Figure 4.4S:



Note the use of diagonal pavement marking to the inside of the Entry Curve. This is to allow for the tracking of the heavy vehicle as it negotiates the R70.3m entry curve, which is greater than the maximum R55 entry path radius as per Section 4.5.3. The diagonal marking provides a tighter left-hand inner edge line for light vehicles to follow, to meet the requirements of Section 4.5.3.

Heavy Vehicle Roundabout Geometry Design Process – (Reverse curve approach):

The process used to create the example geometry shown in Table 4.1.1S and Figure 4.4S is described below, to be read in conjunction with Figures 4.4.1S – 4.4.3S.

Designers may use this process to create alternate geometry for different combinations of design speeds, crossfalls, coefficients of side friction, and design vehicles. The steps are as follows:

1. Draw a straight line at 90 degree angle in the X/Y Plane. This will become the right hand edge line of the approach road prior to the first reverse curve
2. Draw a circle with centre at the end of the line, set radius to travelled path radius of curve 4 (Circulating Carriageway)
3. Offset the straight line from Step 1 up at 1.75m. This will become the travelled path of the approach road prior to the first reverse curve.
4. Construct a circle tangential to the circle from Step 2, and the line from Step 3. Set radius to travelled path radius of Curve 3 (Entry Curve) from Table 4.1.1S
5. Move the circle from Step 4 away from the circulating carriageway circle until a tangent can be constructed between the two circles that matches the length of the straight required from Table 4.1.1S (use trial and error in AutoCAD)
6. Offset the line from Step 3 up at 7m
7. Construct a circle tangential to the circle from Step 5 and the line from Step 6. Set radius to travelled path radius of Curve 2 from Table 4.1.1S
8. Move the circle from Step 7 away from the entry curve until a tangent can be constructed between the two circles that matches the length of the straight required from Table 4.1.1S (use trial and error in AutoCAD)
9. Construct a circle tangential to the line from Step 3 and the circle from Step 8. Set radius to travelled path radius of Curve 1 from Table 4.1.1S
10. Move the circle from Step 9 away from Curve 2 until a tangent can be constructed between the two circles that matches the length of the straight required from Table 4.1.1S (use trial and error in AutoCAD)
11. Trim the circles and join the remaining arcs and tangents to create a centreline path of the full approach geometry, to be used for vehicle swept path analysis. Trim the circulating carriageway curve to include min 180 degrees of the curve.

12. Using vehicle swept path software such as AutoTrack or AutoTURN, apply the heavy vehicle design vehicle to the path created in Steps 1 – 11. Include 0.5m body clearance
13. Using a series of arcs and tangents, trace the swept path of the vehicle along the approach reverse curves, and determine central island radius and circulating carriageway width. These arcs and tangents, with the exception of the outer right hand side of the Entry Curve, will become the edge line marking, and the inner left hand side of the Entry Curve will become the chevron outline for the heavy vehicle tracking allowance
14. Offset the central island circle at half the width of the circulating carriageway. This is the path that a light vehicle will take when circulating the roundabout, in line with Section 4.5.3
15. Draw a line tangential to the circle from Step 14 and the heavy vehicle path Entry Curve
16. Fillet the line from Step 15 to the line from Step 8 at a radius of 55m. This is the path that a light vehicle will take on the entry curve, in line with Section 4.5.3 - Maximum Entry Path Radius
17. Offset the arc from Step 16 1.0m to the inside. This will become the left hand edge line/chevron outline for the Entry Curve
18. Offset the arc from Step 17 3.5m to the outside. This will become the right hand edge line for the Entry Curve
19. Join the arcs from Steps 17 and 18 to the preceding edge line curves, and the central island and circulating carriageway edge using tangential lines
20. Delete the original right hand edge line of the entry curve, and associated preceding and following tangents

Figure 4.4.1S:

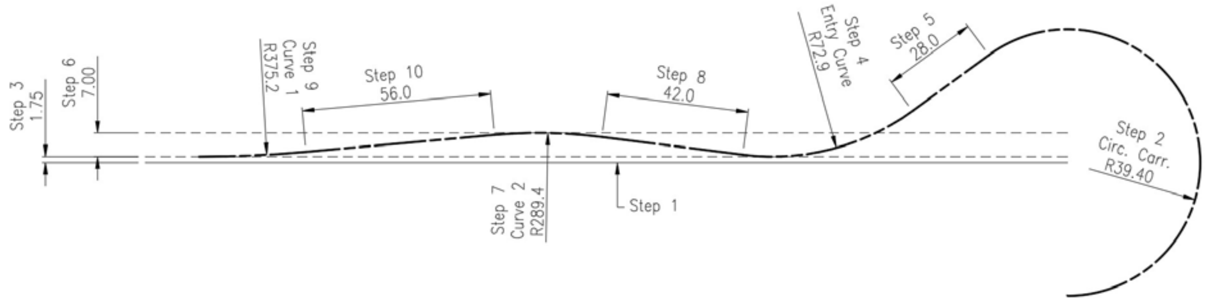


Figure 4.4.2S:

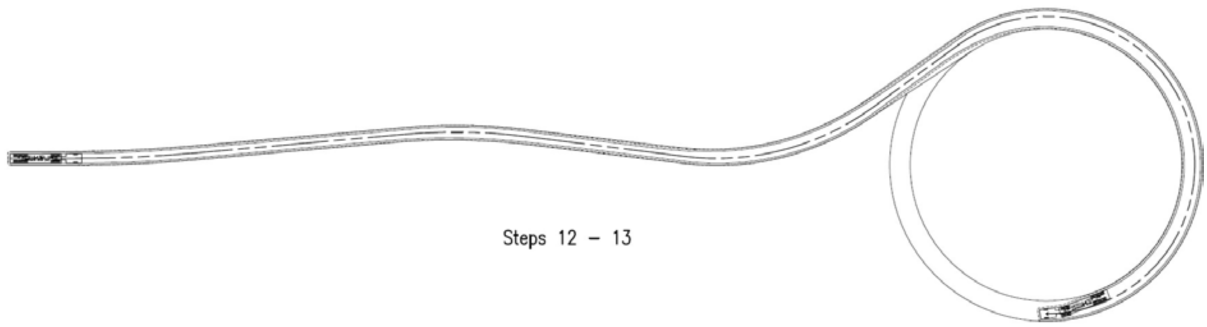
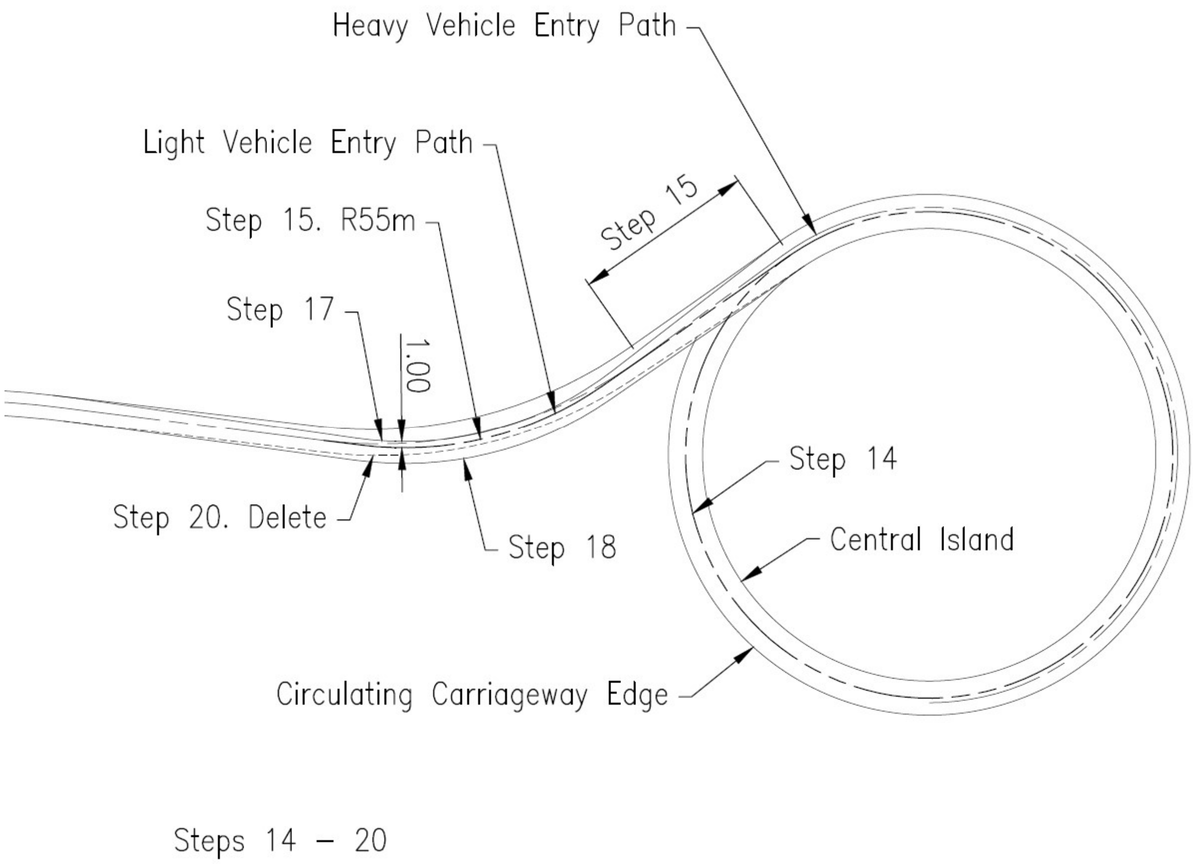


Figure 4.4.3S:



4.5.3 Maximum Entry Path Radius

<u>*Additions:*</u>

Maximum entry path radii criteria is critical to producing lower overall crash rates at roundabouts, due to its speed reduction, and relative angles to circulating vehicle properties.

Due to their lower tolerance of side friction, heavy vehicles typically require larger radii to achieve a given speed, compared to light vehicles.

Heavy Vehicles therefore require larger entry path radii than those listed in Table 4.2, which are predominantly based on light vehicle performance, utilising side friction factors up to f = 0.5.

The process described above in Section 4.5.2 outlines the method to achieve appropriate entry path radii for both light and heavy vehicles.

4.10 Superelevation, Gradient and Drainage

4.10.1 Crossfall

Positive or adverse crossfall

<u>*Additions:*</u>

The recommended crossfall to be used for roundabouts to suit heavy vehicles is 2% adverse, due to the following reasons:

- Adverse crossfall on the second approach curve and the circulating carriageway allows for the pavement to be constructed on a single cross-plane (ignoring the effects of longitudinal grade). This simplifies the constructability, however the principal benefit is that superelevation transitions are not required, which reduces the de-stabilising effects on heavy vehicles, as they rotate from one crossfall to another.
- 2% adverse allows for smaller radii than 3% adverse for a given coefficient of side friction, and also minimises the reduction in horizontal distance between the vehicle's centre of gravity and the overturning hinge point (Refer Austroads (2017) Appendix B for further information)
- Adverse crossfall on the circulating carriageway provides a higher central island with improved visibility compared to superelevated
- Adverse crossfall on the circulating carriageway allows for simpler drainage considerations compared to superelevated

Factors to consider when providing adverse crossfall include:

- Where adverse crossfall curves are utilised, designers need to restrict the coefficient of side friction to 2/3 the maximum recommended, in line with Austroads (2016) Table 7.12, and due to the factors that affect truck stability, outlined in Austroads (2017) Appendix B.3

- 2% crossfall is generally the absolute minimum crossfall to be utilised for asphalt and bitumen sealed pavements, and requires tightly controlled construction tolerances to ensure positive drainage

Where space constraints exist, super-elevated curves including the circulating carriageway may be considered, which may allow the use of smaller radii, however factors to consider include:

- Superelevation transitions, particularly between the entry curve and the circulating carriageway, can have a de-stabilising effect on heavy vehicles as they rotate crossfall from one direction to the other.
- Designers will need to carefully consider the superelevation transitions in accordance with Austroads (2016) and ensure that maximum rates of rotation are not exceeded.

6. Pavement Markings and Signing

Additions:

6.4 High-Speed Rural Roundabout

When catering for heavy vehicles, an increased level of signage is required at high-speed roundabout approaches, to conspicuously alert drivers that they need to reduce their speed prior to negotiating the curves. Without appropriate signage, the reverse-curve approaches, intended to act as speed-reduction devices, can actually become hazardous for heavy vehicles.

Reverse-curve approaches reduce vehicle speeds in line with the Limiting Curve Speed theory of the Operating Speed model. As per Austroads (2016) Section 3.6.1, this model relies heavily on appropriate “driver behaviour”, which, regarding heavy vehicle drivers decelerating for curves, relies on:

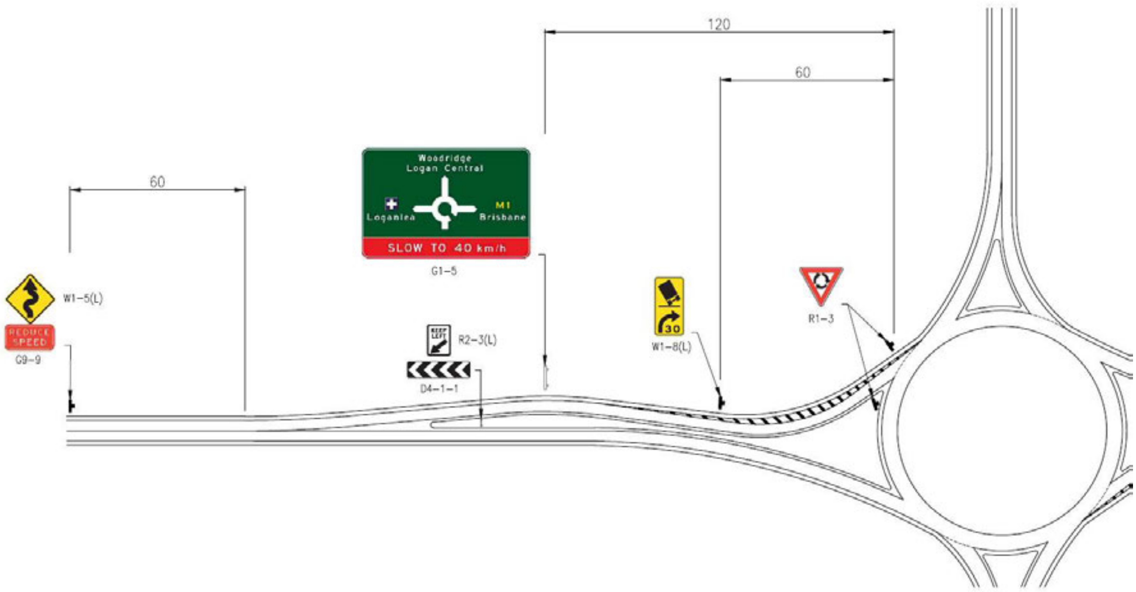
- Drivers visually assessing the curve, and determining what speed is considered safe for the curve ahead
- Decelerating to the appropriate speed for the curve by the start of the curve (unlike car drivers going into the curve)

The limiting curve speed for a given radius can be significantly different depending on if the curve is superelevated, or adverse crossfall. Determination of the crossfall can be difficult to assess visually from the drivers seat.

Therefore, increased signage is recommended to help alert heavy vehicle drivers of the approaching elements and required speeds to negotiate the geometry safely.

Figure 6.3S shows an example of recommended approach signage for a high-speed roundabout where significant heavy vehicle usage is expected:

Figure 6.3S:



Notes:

1. Figure 6.3S example signage is based on the recommended example geometry outlined in Section 4.5.2
2. R1-3, D4-1-1 and R2-3 signs are as per MUTCD Part 2
3. For further information regarding G1-5 sign with supplementary advisory speed plate, refer TMR's TRUM Volume 1 Part 10. Advisory speed to be set to circulating carriageway design speed for light vehicles
4. W1-8 Truck Tilting sign speed to be set to the circulating carriageway design speed for heavy vehicles
5. W1-5 Winding Road and G9-9 Reduce Speed signs to be installed in advance of the first approach curve