



Roundabouts and Traffic Signals

Guidelines for the Selection of Intersection Control



EXECUTIVE SUMMARY

1. INTRODUCTION

The purpose of this document is to provide information to assist practitioners to determine the most appropriate intersection control solution between a roundabout and a signalised intersection. The following aspects are considered:

- Safety performance.
- Operational performance.
- Reliability and accuracy of currently available analytical tools for intersection performance.
- Guidelines for the selection of an appropriate intersection form of control and traffic control in various situations.

Over recent years there has been a growing interest in the selection of roundabouts for intersection control. This has been primarily driven by the recognition that roundabouts provide significant safety benefits for vehicular traffic by slowing down through traffic, reducing the number of conflict points and reducing the angle of potential conflict. From a “Safe System” point of view the roundabout is often viewed as the ideal at-grade intersection option. However, there has also been some concern about the relative performance of these forms of control from an operational point of view.

This guideline document has been developed to provide assistance to traffic engineers and road designers to determine whether traffic signals or a roundabout are the appropriate form of intersection control on major roads carrying higher traffic volumes, such as Primary Distributors, Distributors A & B and Local Distributors.

Based on road hierarchy, at major arterial road intersections with medium and high volumes (Primary Distributor and Distributor A roads) and where grade separation cannot be justified, traffic would generally be controlled by either traffic signals or roundabouts. In WA on the higher order roads roundabouts are considered the most appropriate form of intersection control whereas traffic signals *may* be an appropriate form of control.

2. SAFETY PERFORMANCE OF ROUNDABOUTS AND TRAFFIC SIGNALS

When designed correctly, the roundabout is probably the safest type of intersection for motor vehicles. Based on a summary of crash rates for *all* crash types, intersections controlled by roundabouts have a significantly lower crash rate than intersections controlled by traffic signals. Even where traffic volumes are higher, roundabouts have less than half the crash rate of intersections controlled by traffic signals. Moreover, the summary data generally indicates that the *casualty* crash exposure rate at roundabouts in the Perth Metropolitan Area is approximately twenty five percent less than the *casualty* crash exposure rate of signalised intersections, when averaged across all road environment types.

Evidence suggests that roundabouts are at least as safe for pedestrians as other forms of intersection control; however there appears to be a perception that they are unsafe. It is acknowledged that some pedestrians are concerned about their safety because roundabouts do not give positive priority to pedestrians over through and turning movements and exits are seen as particularly problematical. Because pedestrians can have difficulty using roundabouts, this may also cause confusion between perceptions of safety and level of service. In addition, pedestrians who are sight impaired have greater difficulty assessing traffic movements at roundabouts.

Evidence exists to show that roundabouts are not as safe for cyclists as for other road users, and that signalised intersections are generally safer for cyclists. Specific provision for cyclists is not generally

required at single lane roundabouts on local streets where vehicle speeds are low (i.e. ≤ 50 km/h) and traffic volumes are low (i.e. ≤ 3000 vpd). For larger roundabouts a key factor is the speed at which vehicles can enter and pass through the roundabout.

Where cyclists and pedestrians are expected to use a roundabout, the design speed should be minimised, within the limitations necessary to provide adequate service to other road users. Where a significant number of cyclists and pedestrians use or are expected to use a site, the alternative of providing a signalised intersection should be considered.

3. CAPACITY PERFORMANCE OF SIGNALS AND ROUNDABOUTS

The process of selecting an appropriate intersection control assumes that the preferred control is acceptable from a capacity point of view. If an acceptable operational efficiency cannot be practically achieved for a particular type of intersection control, this would constitute a “fatal flaw”.

SIDRA INTERSECTION has traditionally been used as the primary tool to analyse the capacity and operating performance of traffic signals, roundabouts and other non-signalised intersections in WA. More recently, Main Roads has started using LINSIG as an analysis and optimisation tool, particularly for signalised intersections, arterial routes and networks. Both SIDRA and LINSIG have been proven to provide accurate analyses, when assessed by experienced professionals.

Micro-simulation software such as VISSIM and PARAMICS are also used to analyse roundabouts and traffic signals. However, it should be borne in mind that these micro-simulation tools are a lot more time consuming and costly and should generally only be used if a demonstration is needed for community consultation or other stakeholder purposes.

4. FACTORS AFFECTING THE CHOICE OF FORM OF CONTROL FOR ROUNDABOUT OR TRAFFIC SIGNAL INTERSECTIONS

The objective when choosing a form of control for an intersection should be a cost effective control that balances the safety, operational efficiency and amenity needs of all road users. In the past there has been a focus primarily on the capacity analysis, or the operational performance of the intersection type. However, this should be viewed as only one factor, and provided that an acceptable operational performance is achievable, then the following additional factors need to be considered:

| | |
|--------------------------------|---|
| General Factors – | Safety, Cost, Economic Evaluation, Community views & consultation. |
| Site Specific Factors – | Physical controls, Road environment, Road users, Traffic Management considerations. |

General Factors

The **safety** of an intersection needs to be a key input when selecting a treatment or type of intersection control. Main Roads has adopted “The Road Towards Zero” Road Safety Strategy which aims to eliminate death and serious injury on the Western Australian road network. A key component of this strategy is the adoption of Safe System procedures, practices and programs. One of the cornerstone components of the Safe System approach is to reduce speeds at intersections so that any potential right-angle conflicts would be limited to a speed of 50 km/h. At that speed the likelihood of a motorist surviving a crash of this nature is 90%.

Research indicates that roundabouts are generally safer when compared with signalised intersections. Therefore, where signals are chosen at a site, it is generally accepted that there needs to be a balance between safety and other important factors at the site. To maximise safety on the road network, a roundabout would generally be the preferred option unless entry speeds can be reduced to 50 km/h or less, and unless other factors make a roundabout option inappropriate.

The stability and acceleration / deceleration characteristics of multi-combinational vehicles need careful consideration in relation to safe passage through a rural roundabout.

The initial **cost** of a control proposal may include (a) land acquisition, (b) relocation of utilities, and (c) construction costs. The cost may also be influenced by the degree to which a proposal is to be compatible with staging of longer term works.

The **economic evaluation** relating to a decision on control options under consideration needs to quantify and compare the anticipated benefits for each option (positive and negative) and costs discounted over the life of the control. The factors to be considered generally include (a) safety performance, (b) capacity performance, (c) initial cost, and (d) recurrent costs. Typically a project life of 10 years after opening should be adopted.

Community views and consultation - The views of the Local Government Authority relating to community needs and preferences are key inputs to the decision making process. Inputs in relation to freight and public transport needs are also important. In some situations the views of the community or stakeholder groups (eg. a chamber of commerce or heavy vehicle operators) may also be desirable.

Site Specific Factors

A summary of the various site specific factors is provided in Table X.1. This table is designed as a “quick reference” guide and should not be treated as definitive. For example any proposed signalised intersection in a rural area will be labelled as “unlikely” to be an appropriate type of treatment. This does not automatically preclude it as a possible treatment since most issues can be “engineered out”, albeit at a cost.

| Site Specific Factors | Signals | Roundabout |
|---|--|---|
| Physical Controls <ul style="list-style-type: none"> Number of intersection legs Number of through lanes Space available Site topography Access to adjacent properties | M – Up to maximum of 4 L – Up to 3 M – subject to design M – subject to design M – subject to design | M – Up to maximum of 6 L – Up to 2. M/U – Up to 3 – subject to design M/U – subject to design (may be difficult in Brownfield sites) M/U – subject to design (may be difficult in hilly terrains) M – subject to design |
| Road Environment <ul style="list-style-type: none"> Rural area Outer urban or fringe areas Inner urban area High speed approaching traffic | U M L M – May consider with 80 km/h speed limit & warning signs / flashing lights | L L M L - with design features to control approach speed |
| Road Users <ul style="list-style-type: none"> Pedestrian needs <ul style="list-style-type: none"> Children, the elderly and the disabled Significant number of other pedestrians | L L | U – unless pedestrian signals provided M - consider pedestrian facilities, low design speed and spare capacity |

| | | |
|---|--|--|
| <ul style="list-style-type: none"> Bicyclists needs <ul style="list-style-type: none"> Significant number of children or recreational cyclists Significant number of other cyclists Needs of large vehicles | L L L | U – unless off-road facility and pedestrian signals provided M – with low speed design M/U – may be difficult with high volumes & high % heavies |
| Traffic Management <ul style="list-style-type: none"> Route or area strategies <ul style="list-style-type: none"> Adjacent to linked signals Isolated locations Adjacent sites controlled with roundabouts Control of traffic through a local area Traffic volumes and capacity <ul style="list-style-type: none"> Balanced flows Unbalanced flows Significant turning volumes Minimising off-peak delays Public transport <ul style="list-style-type: none"> (Light Rail) Trams Buses Adjacent to a railway level crossing | L M M L M M U L L L | U L L U M M – with metering signals L L U |

Legend:

L - Likely to be an appropriate form of control

M - May be an appropriate form of control

U – Unlikely to be an appropriate form of control

Table X.1: Summary of Specific Factors and Form of Intersection Control Choice

Road Users

Needs related to pedestrians - pedestrians are unprotected road users and therefore are generally at greater risk than road users in motor vehicles. In high traffic volume locations, pedestrians generally prefer to use traffic signals as these provide priority with a pedestrian signal phase and separation from through traffic flows. While crash data at roundabouts generally indicates that there is not a particular safety problem for pedestrians, there is a general dislike for roundabouts by pedestrians and a perceived safety risk as they may be difficult to cross.

Where a roundabout is being considered in an environment with pedestrians, consideration should be given to incorporating a range of design features, including:

- Pedestrian signals across the approaches - to provide for children, elderly persons or pedestrians with disabilities.
- Pedestrian (zebra) crossings or pedestrian signals across approaches.
- A lower design speed than usual, generally 40 km/h.
- Good visibility.
- Adequate vehicular capacity.

Needs related to cyclists - Crash data generally indicates that there is a safety problem for cyclists at roundabouts. At traffic signals a cyclist's mobility needs relate primarily to sharing road space. In an area with significant bicycle usage (particularly children or recreational cyclists), preference may need to be given to traffic signal forms of control with specific provisions such as bicycle lanes, advanced stop lines and storage areas.

Where bicycles are expected to use a site where a roundabout is the preferred form of control, a number of provisions need to be considered including:

- Low design speed (generally 30 to 40 km/h).
- Avoiding squeeze points for cyclists on the approach and through the roundabout.
- Provision for cyclists to move off the carriageway to use shared paths around the outside of the roundabout, particularly at locations used by children or recreational cyclists.

Needs of large vehicles - Signalised intersections are considered to provide a more convenient treatment for the drivers of large trucks than roundabouts, depending on the characteristics of the particular intersection. While trucks at times will encounter the inconvenience of coming to a complete stop at a red signal, they are often able to continue through a green signal. This is generally preferred to the inconvenience associated with negotiating a roundabout where multi-combinational vehicles struggle to “pick a gap” when the circulatory traffic is high due to poor acceleration characteristics.

When considering heavy vehicles, particularly multi-combinational vehicles, the success of implementing a roundabout will be highly dependent on the truck driver’s ability to pick a gap in the circulating traffic. This is greatly influenced by the circulating traffic volumes as well as the roundabout geometry; good sight distance is essential for truck drivers to be able to adjust their approach speeds to suit the gaps in the circulating traffic. This also highlights the importance that any capacity analysis makes suitable adjustments to the percentage heavy vehicles as well as gap acceptance parameters and follow-up headways for heavy vehicles.

In rural areas intersections on major roads and highways should be designed to cater for a 36.5m A-double road train as a minimum. The design should also cater for 53.5m A-triple road trains if the Main Road’s Region permits use of these vehicles.

Where large or special vehicles are expected to use a site where a roundabout is the preferred form of control it is important to:

- Provide appropriate space for the swept path of large vehicles.
- Provide truck stopping sight distance, understanding that at roundabouts it is difficult for drivers of multi-combinational vehicles to “pick a gap” – consequently it is important that if the design vehicle is an A-double, or larger, all three sight distance criteria given in the Austroads Roundabout Guidelines must be satisfied. If the design vehicle is a 19.0m semi-trailer, then only criteria 1 & 2 must be satisfied.
- Consider vehicle stability for turning movements by providing radii appropriate for the turning speeds and providing a satisfactory crossfall and a uniform rate of change of crossfall. This is particularly important for multi-combinational vehicles where the prime mover and trailer(s) may be on different crossfalls at the same time.

Traffic Management

Capacity Analysis - for new (Greenfield sites) intersections, the following performance criteria should apply to the analysis based on traffic volumes in the target year:

The overall LOS for intersections during peak periods should be Level “C” or higher, with no individual major movement having a LOS lower than Level “D” and no individual minor movement having a LOS lower than Level “E”. Moreover, no individual movement should have a DOS greater than the following:

- | | |
|---------------------------------|------|
| • Signalised intersections | 0.90 |
| • Roundabouts | 0.85 |

For existing (Brownfield sites) intersections, similar performance criteria should apply for the DOS but the LOS may need to be based on the best achievable, given the site constraints.

A sensitivity analysis to consider the implications of higher volumes may need to be considered where there is uncertainty regarding design volumes or future traffic growth.

Roundabouts generally provide significant advantages over traffic signals in minimising delays during off peak periods. An economic evaluation may be based on calculated delays for the peak periods, but may also consider the operation during off peak operation. A ‘whole of day’ analysis provides a more precise assessment of benefits / disadvantages. Lower off peak delay during the day is particularly beneficial for business travel and freight.

5. USE OF TRAFFIC SIGNALS AND ROUNDABOUTS AT INTERCHANGES

To date in WA there has been limited use of roundabouts as junctions at service interchanges. However, with the increased “Safe System” approach to intersection design, it is recognised that roundabouts can offer significant safety advantages over signalised intersections. Commentary 2 summarises the advantages and disadvantages of various types of service interchanges using either traffic signals or roundabouts as the form of intersection control.

6. TRAFFIC SIGNALS AT ROUNDABOUTS

Although the combination of traffic signals with roundabouts is not the main focus of this document, information has been provided in relation to the operation of traffic signals in conjunction with roundabouts. Moreover if the capacity analysis indicates that the residual capacity in the target horizon year is small and there is a strong possibility of full signalisation being required, then the initial design should take into account the need to provide for internal queueing in the future and the size of the roundabout should be designed accordingly. Any proposed change in intersection operational types should also check the suitability of the change for all expected vehicle operating characteristics.

The full signalisation of roundabouts can have a positive effect on some crash types. The partial signalisation of roundabouts (metering signals) can also have a positive effect due to increased capacity, although there may be a potential for increased rear-end crashes due to drivers becoming confused about two holding lines, (i.e. stop line at signals followed closely by holding line at roundabout entry). This may be mitigated by ensuring there is sufficient distance between the traffic signal stop line and the roundabout Give Way line. In addition, the use of two-aspect signals (red and amber) assists in preventing drivers from mistakenly driving through a green signal and failing to give way at the downstream give way line.

Partial Signalisation (Metering Signals) at Roundabouts

Roundabout performance is sensitive to unbalanced traffic flows, however this deficiency may be addressed by the provision of part time metering signals that regulate the dominant flow and provide gaps in the circulating traffic. Metering signals provide the following benefits:

- Management of the peak flows to provide appropriate priority for a major movement.
- Provide better balance of queues and delays between approaches.
- They can extend the life of a roundabout rather than require its replacement.
- The provision of metering signals can also be beneficial for pedestrians, as the metering system can be combined with pedestrian signals to provide a pedestrian facility across a leg (or legs) of a roundabout.

Full Signalisation of Roundabouts

In the full signalisation of a roundabout, the signals control both entering traffic and circulating traffic at each entry but are not used to control traffic that is exiting from the circulating roadway. One of the major advantages of signalising a roundabout from a capacity point of view is that, in its simplest form, each signalised junction can be operated on a two-phase system. However, for full signalisation to be successful, the roundabout must be sufficiently large to accommodate any necessary queuing in the circulating roadway, or be of such a size that it can be operated without excessive lost time.

Furthermore the cycle length should be comparatively short (50 to 60 seconds is preferred) to limit the internal queue lengths arising from the right turning traffic.

Future of Signal Control at Roundabouts in WA

Signalisation of roundabouts is used extensively in the United Kingdom to improve capacity, reduce delays, reduce crashes and address pedestrian and cyclist difficulties. More detail on signalised roundabouts in the UK is provided in Commentary 3.

Roundabout metering signals (indirect control) - Based on the success of the implementation of roundabout metering signals at Point Lewis Rotary (and the proven effectiveness at a number of sites elsewhere in Australia), the use of metering signals would appear to have significant potential. Recent additions to the SIDRA INTERSECTION analysis program have enhanced its ability to analyse roundabouts with one or more legs metered. This form of control could be operated under part-time control - where the signals are switched on or off at set times (generally peak periods) or under certain traffic conditions by queue detectors.

Direct Signal Control – There is no doubt that the full signalisation of the Eelup Rotary has been an outstanding success, both from a safety and operational perspective. However, because of the internal storage requirements, it may only be feasible to provide direct signal control at large roundabouts, which limits its applicability.

Direct signal control warrants further investigation and assessment to determine its potential to improve the operation of roundabouts in WA. This form of control may be a solution to addressing delays at congested sites where indirect signal control may not be appropriate. If direct signal control is able to provide the benefits achieved in the UK, this may avoid significant costs to replace roundabouts with signals.

However, further investigation would be needed to determine the suitability of implementing part-time direct signal control, especially in the light of the UK experience that it could lead to potential safety problems, no provision for pedestrians and cyclists and a compromised layout. Nevertheless, it may be advantageous to retain the operational benefits of roundabouts at off peak periods provided the roundabout can cater for the types of multi-combinational vehicles expected to use the roundabout.

7. PROCESS FOR CHOOSING INTERSECTION CONTROL TYPE

The consideration and balancing of the site specific items shown in Table X.1, as well as appropriate analyses and evaluation, are essential parts of determining an appropriate form of control for an intersection.

The philosophy adopted in these guidelines for choosing between traffic signal control and roundabout control has been to balance all the relevant factors to arrive at the most cost effective solution that meets all (or the most) relevant criteria. However, given that from a Safe System point of view a

roundabout design minimises the number and severity of vehicular conflicts and hence is considered the safer of the two options, it is suggested that the design process start with the assumption that a roundabout is the preferred traffic control type (unless the design can be shown to offer similar safety characteristics as a roundabout) and only if it cannot meet all necessary design requirements should traffic signal control be considered.

The type of intersection control can have a significant impact on the amount of land required as well as access to and from adjacent properties. For these reasons it is important that the intersection control type be determined early on in the planning or design process in order to define or redefine appropriate cadastral boundaries. Under certain constrained conditions, an initial analysis of options may be sufficient to eliminate any intersection control types as “fatal flaws”, although as a minimum it will generally be necessary to take the option(s) to a concept design stage. In some cases it will be necessary to take the concept design to a preliminary design standard.

Flow Chart X.1 should be used to determine the appropriate control type for intersections on major roads. The outcome from this process will either be that roundabout control is suitable or that the designer should follow Flow Chart X.2 to determine a suitable signalised layout. During the process relevant checks are made to ensure that all general and site specific factors identified previously are considered and are satisfactorily addressed.

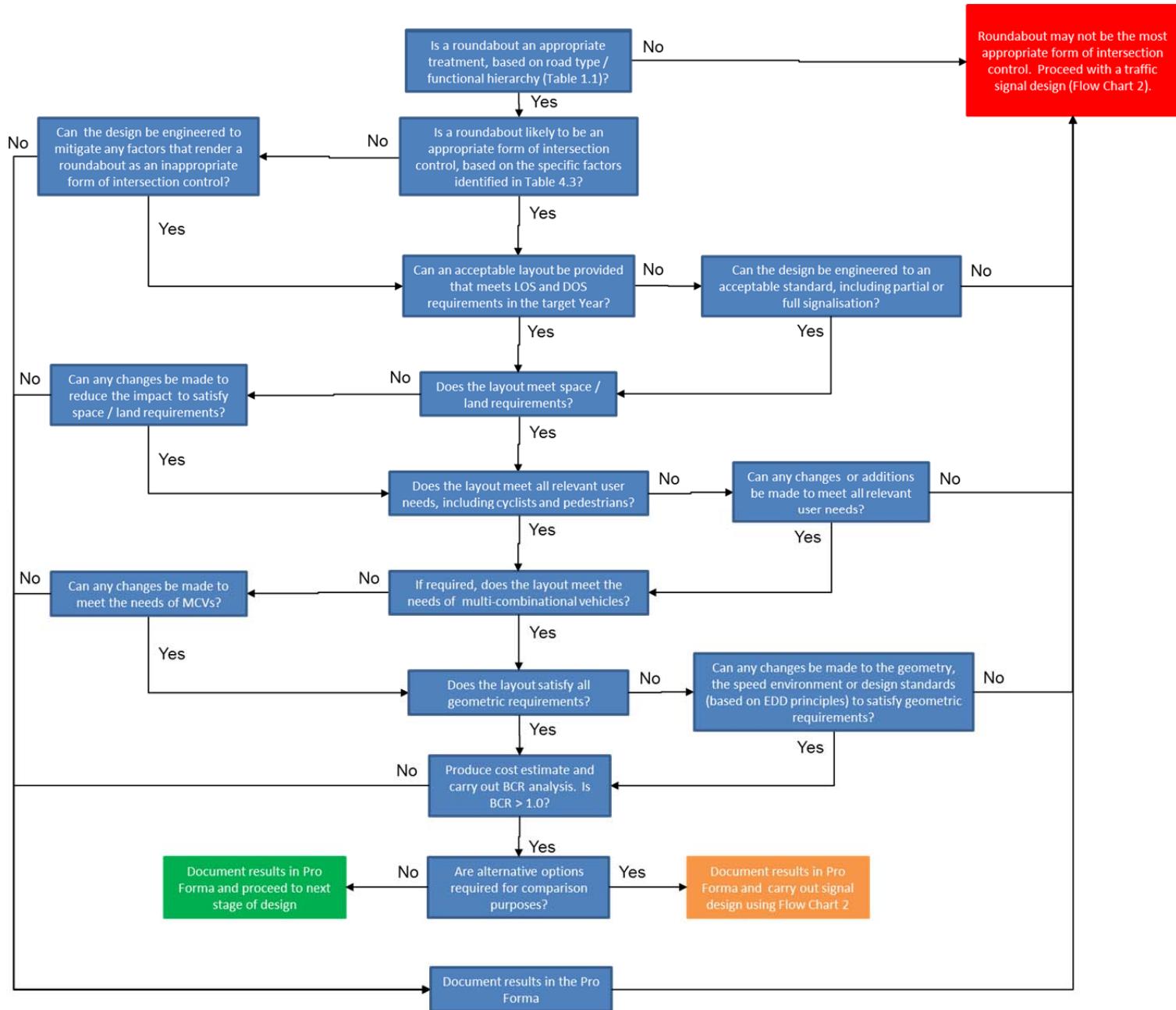


Figure X.1: Flow Chart 1 – Process for Choosing between Roundabout and Traffic Signal Control

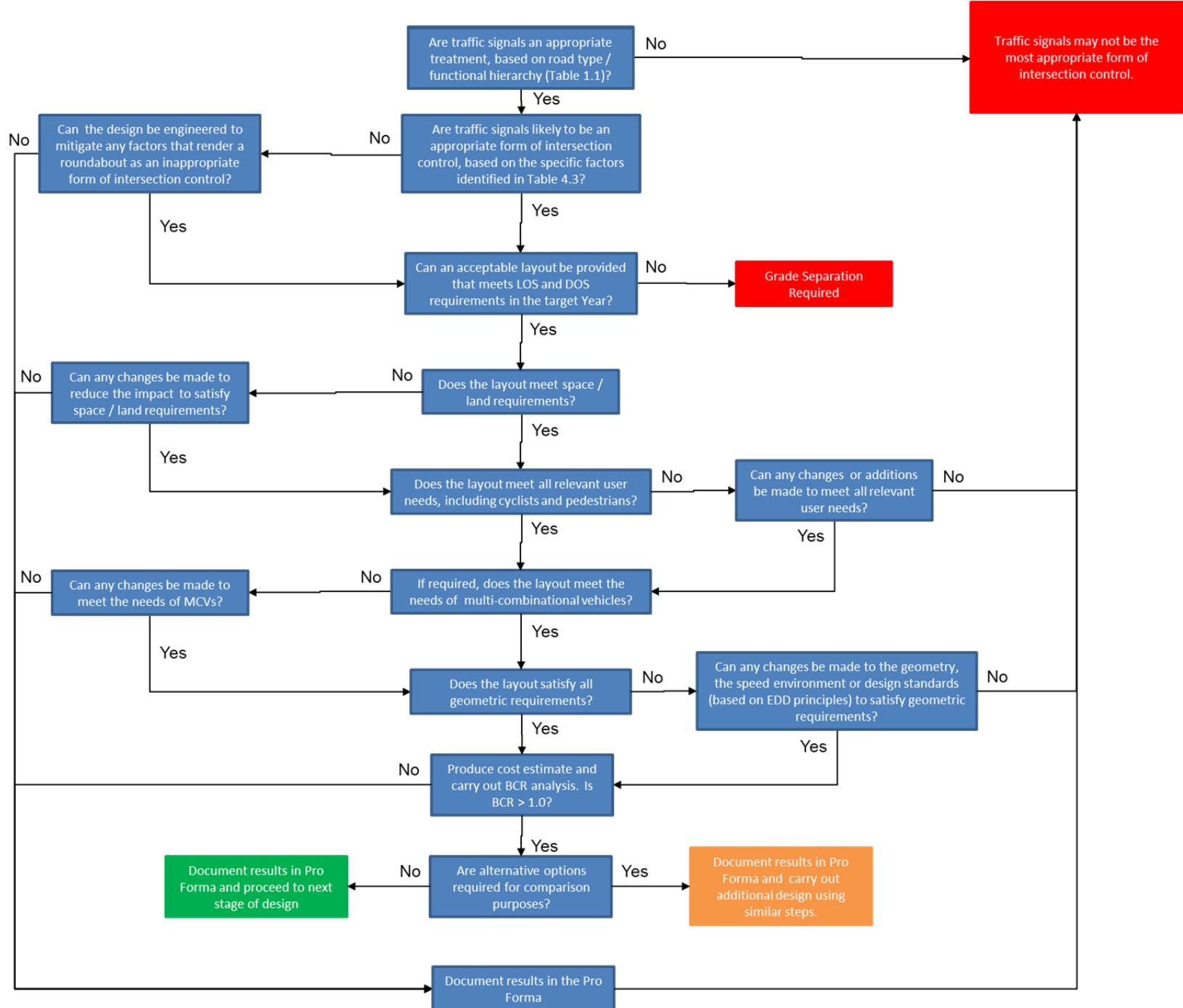


Figure X.2: Flow Chart 2 –Traffic Signal Control Design Process

CONTENTS

| | | |
|--------|--|----|
| 1. | Introduction..... | 1 |
| 1.1 | Overview..... | 1 |
| 1.2 | Purpose of this Guideline Document..... | 2 |
| 2. | Safety Performance of Roundabouts and Traffic Signals | 3 |
| 2.1 | Crash Frequencies..... | 3 |
| 2.2 | Crash Rates – Exposure Relative to Traffic Volumes | 3 |
| 2.3 | Pedestrian Safety at Roundabouts | 4 |
| 2.4 | Cyclist Safety at Roundabouts | 4 |
| 2.5 | Why are Roundabouts Safer for Vehicles? | 5 |
| 3. | Capacity Performance of Signals and Roundabouts..... | 7 |
| 3.1 | Accuracy of Current Analytical Tools..... | 7 |
| 3.2 | Reliability of Capacity Analyses | 7 |
| 4. | Factors Affecting the Choice of Form of Control for Roundabout or Traffic Signal Intersections | 9 |
| 4.1 | Balancing the Factors to be Considered | 9 |
| 4.2 | General Factors..... | 10 |
| 4.2.1. | Safety | 10 |
| 4.2.2. | Costs | 10 |
| 4.2.3. | Economic Evaluation..... | 10 |
| 4.2.4. | Community Views and Consultation | 11 |
| 4.3 | Physical Controls..... | 12 |
| 4.3.1. | Number of Intersection Legs and Angle between Legs..... | 12 |
| 4.3.2. | Number of Lanes through the Intersection..... | 13 |
| 4.3.3. | Space Available | 13 |
| 4.3.4. | Site Topography | 15 |
| 4.3.5. | Access to Adjacent Properties | 15 |
| 4.4 | Road Environment | 16 |
| 4.4.1. | Rural, Outer Urban and Inner Urban Areas..... | 16 |
| 4.4.2. | Speed of Approaching Traffic | 17 |
| 4.4.3. | Adjacent Land Use | 17 |
| 4.5 | Road Users | 17 |
| 4.5.1. | Needs related to Pedestrians | 17 |
| 4.5.2. | Provision for Pedestrians at Roundabouts | 18 |
| 4.5.3. | Needs related to Cyclists | 19 |
| 4.5.4. | Provision for Cyclists at Roundabouts | 20 |

| | |
|---|----|
| 4.5.5. Needs of Large Vehicles..... | 21 |
| 4.5.6. Provision for Large Vehicles at Roundabouts | 23 |
| 4.6 Traffic Management | 24 |
| 4.6.1. Route or Area Strategies..... | 24 |
| 4.6.2. Road Hierarchy, Local Access and Amenity | 25 |
| 4.6.3. Traffic Volumes and Traffic Signal Warrants | 25 |
| 4.6.4. Capacity Analysis | 26 |
| 4.6.5. Project Life | 29 |
| 4.6.6. Public Transport – Light Rail (Trams) or Buses | 29 |
| 4.6.7. Public Transport – near Railway Level Crossings..... | 29 |
| 4.7 Summary of Site Specific Factors and Form of Control Choice | 30 |
| 5. USE OF TRAFFIC SIGNALS AND Roundabouts AT INTERCHANGES | 31 |
| 6. Traffic Signals at Roundabouts | 31 |
| 6.1 Partial Signalisation (Metering Signals) at Roundabouts | 31 |
| 6.1.1. General Provisions | 31 |
| 6.1.2. Provisions for Pedestrians at Roundabouts with Metering Signals..... | 32 |
| 6.1.2. Warrants for Roundabout Metering Signals..... | 35 |
| 6.2 Full Signalisation of Roundabouts | 37 |
| 6.3 Future of Signal Control at Roundabouts in Western Australia | 38 |
| 7. Process for Choosing Intersection Control Type | 39 |
| 8. REFERENCES..... | 42 |
| 9. COMMENTARIES..... | 43 |

1. INTRODUCTION

Over recent years there has been a growing interest in the selection of roundabouts for intersection control. This has been primarily driven by the recognition that roundabouts provide significant safety benefits for vehicular traffic by slowing down through traffic, reducing the number of conflict points and reducing the angle of potential conflict. From a “Safe System” point of view the roundabout is often viewed as the ideal at-grade intersection option. However, there has also been some concern about when roundabouts or traffic signal control may be appropriate and the relative performance of these forms of control from an operational point of view.

This guideline document has been developed to provide assistance to traffic engineers and road designers to determine whether traffic signals or a roundabout are the appropriate form of intersection control on major roads carrying higher traffic volumes, such as Primary Distributors, Distributors A & B and Local Distributors. It is presumed that the traffic volumes would be too high for unsignalised intersections to be an appropriate form of intersection treatment; hence a comparison between roundabouts and unsignalised intersections is not discussed in this document.

Main Roads acknowledges that this document is based on the VicRoads “Traffic Management Note No. 22 – November 2005”, but has been customised to suit Western Australian circumstances and needs. As such Main Roads WA takes full responsibility for the content of this document.

1.1 Overview

Intersections play a significant role in the operation of the road network. Where two or more roads meet or cross, the intersection controls the amount of traffic able to use the intersecting roads and together with the capacity of the road links themselves, provides a significant contributing factor in determining the capacity of the road network as a whole. Generally, in urban areas, the intersection capacity controls the capacity of the road network.

The crossing and turning movements at intersections need to be appropriately managed to ensure that safety and operational efficiency are optimised. Generally, appropriate intersection control depends on traffic and site needs that may rely on giving way at a T-intersection, regulatory signs (Stop or Give Way), roundabouts, traffic signals or grade separations. These forms of control may also be provided with appropriate layout design and channelisation to control vehicle movements and points of conflict.

Table 1.1 over the page provides a broad guide to the suitability of the type of traffic control in relation to functional classification of roads (Austroads, 2013). The functional classification for WA roads is available internally through the Integrated Mapping System by ticking the “Road Hierarchy” box under “Classification” in the Catalogue.

The table is based on the general appreciation of the need to provide a satisfactory level of mobility on arterial roads. In some cases the suitability is obvious; in other cases traffic analyses and examination of other factors will be necessary to determine the most appropriate form of control at a site.

From Table 1.1 it can be seen that at major arterial road intersections with medium and high volumes (Primary Distributor and Distributor A roads) and where grade separation cannot be justified, traffic would generally be controlled by either traffic signals or roundabouts. In WA on the higher order roads roundabouts are considered the most appropriate form of intersection control whereas traffic signals *may* be an appropriate form of control.

| | Primary Distributor (excluding Freeways) | Distributor A | Distributor B & Local Distributor | Access Road |
|--|---|---------------|--------------------------------------|-------------|
| Traffic Signals | | | | |
| Primary Distributor (excluding Freeways) | O | O | O | X |
| Distributor A | O | O | O | X |
| Distributor B & Local Distributor | O | O | X | X |
| Access Road | X | X | X | X |
| Roundabouts | | | | |
| Primary Distributor (excluding Freeways) | A | A | X | X |
| Distributor A | A | A | A | X |
| Distributor B & Local Distributor | X | A | A | O |
| Access Road | X | X | O | O |
| STOP signs or GIVE WAY signs | | | | |
| Primary Distributor (excluding Freeways) | X / (O) | X / (O) | A | A |
| Distributor A | X / (O) | X / (O) | A | A |
| Distributor B & Local Distributor | A | A | A | A |
| Access Road | A | A | A | A |
| Legend: | | | | |
| A = Most likely to be an appropriate treatment | | | | |
| O = May be an appropriate treatment | | | | |
| X = Usually an inappropriate treatment | | | | |

Source: Adapted from (Austroads, 2013)

Table 1.1: Suitability of Types of Traffic Control to Different Road Types

1.2 Purpose of this Guideline Document

The purpose of this document is to provide information to assist practitioners to make an objective comparison between roundabouts and traffic signals for the purpose of intersection control-type selection. The following aspects are considered:

- Safety performance.
- Operational performance.
- Reliability and accuracy of currently available analytical tools for intersection performance.
- Guidelines for the selection of an appropriate intersection form of control and traffic control in various situations.

The guideline relates to Primary Distributor roads (excluding freeways), Distributor A, B and Local Distributor roads in urban and rural environments. Although some of the principles may also be relevant to local access road intersections, this is not the intended focus of the document.

The guideline provides information and additional guidance in relation to design and choice of form of control involving roundabouts and traffic signals. Reference should also be made to current Main Roads and/or Austroads guidelines for design details and other supporting information.

2. SAFETY PERFORMANCE OF ROUNDABOUTS AND TRAFFIC SIGNALS

2.1 Crash Frequencies

Typical crash rates for similar types of intersections can provide a basis for assessing safety performance in the following ways:

- A comparison of performance for intersections of differing types or traffic control.
- A benchmark against which a specific intersection can be compared.

Summary statistical data for the five year period 2009 to 2013 for the Perth Metropolitan Area provides averaged safety performance data for road intersections controlled by roundabouts and traffic signals. These average rates may be used to compare a specific intersection with the network wide averages appropriate to the road environment. The safety performance rates for different road types in different environments for all crash types are summarised in Table 2.1. It should be noted that while these figures are based on limited data, similar trends have been observed in Victoria.

| | | Mean Crash Frequency for All Crash Types (Crashes / Intersection / Year) | | |
|---------------------------------------|--|---|-------------|------------|
| State Road / State Road Intersections | | Traffic Signals | Roundabouts | Ratio TS/R |
| Inner Metropolitan Area ¹ | | 17.6 | 4.4 | 4.0 |
| Outer Metropolitan Area ² | | 11.2 | 4.6 | 2.4 |
| | | | | |
| State Road / Local Road Intersections | | | | |
| Inner Metropolitan Area | | 13.6 | 0.2 | 68 |
| Outer Metropolitan Area | | 13.2 | 0.8 | 16.5 |
| | | | | |
| Local Road / Local Road Intersections | | | | |
| Inner Metropolitan Area | | 8.2 | 1.2 | 6.8 |
| Outer Metropolitan Area | | 8.2 | 1.6 | 5.1 |

Notes:

- Inner Metropolitan Area: Bassendean, Bayswater, Belmont, Canning, Claremont, Cottesloe, Fremantle, Melville, Nedlands, Perth, Stirling, South Perth, Subiaco, Cambridge
- Outer Metropolitan Area: Armadale, Kalamunda, Cockburn, Gosnells, Rockingham, Swan, Wanneroo, Joondalup, Mundaring, Kwinana, Serpentine-Jarradale

Table 2.1: Summary of All Crash Type Rates in Perth Metropolitan Area

From the above table it is quite clear that intersections controlled by roundabouts have a significantly lower crash rate than intersections controlled by traffic signals. Even where traffic volumes are higher, roundabouts have less than half the crash rate of intersections controlled by traffic signals.

2.2 Crash Rates – Exposure Relative to Traffic Volumes

When crash frequencies are related to traffic volumes using the intersections, they provide a measure related to exposure and traffic use.

The mean safety performance rates for different intersection types for casualty crashes only are summarised in Table 2.2. In this case the crash rates are per million entering vehicles.

| Mean Casualty Crash Rate (Casualty Crashes / Intersection / Year / 10^6 entering vehs) | |
|---|-------------|
| Traffic Signals | Roundabouts |
| 0.20 | 0.15 |

Table 2.2: Summary of Casualty Crash Exposure Rates in Perth Metropolitan Area

The summary data generally indicates that the casualty crash exposure rate at roundabouts in the Perth Metropolitan Area is approximately twenty five percent less than the casualty crash exposure rate of signalised intersections, when averaged across all road environment types. It should be noted that a similar trend was observed in Melbourne (VicRoads, 2005), where the crash exposure rate for roundabouts was typically 20 – 25% less than for signalised intersections.

2.3 Pedestrian Safety at Roundabouts

Evidence suggests that roundabouts are at least as safe for pedestrians as other forms of intersection control possibly because pedestrians are able to cross one direction of traffic at a time by staging on the splitter islands. A Review of Pedestrian Safety at Roundabouts (Charmaine Tumber, 1997) was carried out by VicRoads in 1997. The review considered available investigations and literature from Australia and overseas as well as an evaluation of data for roundabouts constructed on arterial roads in the Melbourne metropolitan area over the period 1987 – 1994.

The review concluded that there is not a demonstrated safety problem for pedestrians at roundabouts. The Melbourne data indicated that there is an average of 0.02 pedestrian crashes per roundabout per year at roundabouts. The findings also indicated that the severity of crashes involving pedestrians is lower than for other forms of control at intersections.

Although available information indicates that roundabouts are relatively safe for pedestrians, there appears to be a perception that they are unsafe. It is acknowledged that some pedestrians are concerned about their safety because roundabouts do not give positive priority to pedestrians over through and turning movements. Exits are problematic, particularly for elderly pedestrians and children who may consider that traffic signals provide greater security for them to cross the road. In addition, pedestrians who are sight impaired have greater difficulty assessing traffic movements at roundabouts.

Because pedestrians can have difficulty using roundabouts, this may also cause confusion between perceptions of safety and level of service. Section 4.5.2 discusses various design features that should be considered in relation to pedestrians and roundabout use.

2.4 Cyclist Safety at Roundabouts

Evidence exists to show that roundabouts are not as safe for cyclists as for other road users, and that traffic signals are generally safer for cyclists.

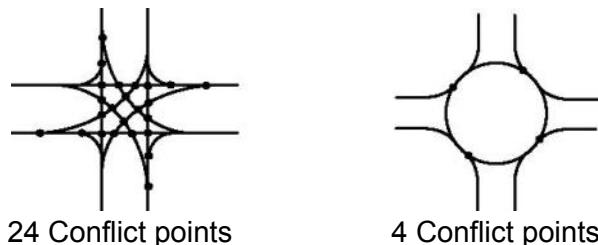
The size and layout of roundabouts is a factor in safety for cyclists. In general, small roundabouts with relatively low traffic speeds, and with a circulating roadway narrow enough to prevent motor vehicles overtaking cyclists, present no special risks for cyclists (The Plan for Cycling is to Encourage it, 1992) (Bruede U. & Larsson J., 1996) (Van Minnen, 1996). Studies have shown that a large proportion of cyclist crashes (about 50%) involve an entering motor vehicle colliding with a cyclist on the circulating roadway. This suggests that entering drivers have difficulty in detecting the presence of cyclists as they scan for larger vehicles that are approaching from their right.

Specific provision for cyclists is not generally required at single lane roundabouts on local streets where vehicle speeds are low (i.e. ≤ 50 km/h) and traffic volumes are low (i.e. ≤ 3000 vpd). For larger roundabouts a key factor is the speed at which vehicles can enter and pass through the roundabout. Where cyclists and pedestrians are expected to use a roundabout, the design speed should be minimised, within the limitations necessary to provide adequate service to other road users. Where a significant number of cyclists and pedestrians use or are expected to use a site, the alternative of providing a signalised intersection should be considered. Section 4.5.4 discusses various design features that should be considered in relation to cyclists and roundabout use.

2.5 Why are Roundabouts Safer for Vehicles?

When designed correctly, the roundabout is probably the safest type of intersection for motor vehicles. The following features generally contribute to the high standard of safety of roundabouts:

- Low operating speed. Slow moving traffic means low energy / low severity crashes and can also enable a driver to avoid a collision. Traffic at a roundabout is initially slowed down by the curved approach and the provision of the splitter island. The location of the central island then physically deflects the traffic through the intersection and controls the speed of traffic.
- Elimination of high angles of conflict thereby ensuring low relative speeds between conflicting vehicles. The roundabout layout limits the types of crashes and angle of impact. This results in low severity crashes in the event of a collision because traffic is moving in the same general direction at a low relative angle ie. significantly reducing the incidence of head-on or right angle crashes.
- Fewer and further separated conflict points. A conflict point occurs where two travel paths merge or cross. Roundabout layouts satisfy safe intersection design principles in relation to conflict points as they minimize the number of conflict points and separate the areas of conflict as demonstrated in the following diagram.



Traffic signal phasing separates major conflicting movements in time, so this reduces some conflict situations. However, this is less effective in preventing crashes than physically restricting vehicle conflicts. At signals, crashes may also occur at controlled conflict situations when a vehicle travels through a red light.

A large area of conflict can occur where wide roads or offset crossroads intersect or when roads intersect at an acute angle. Roundabout layouts minimise conflict areas and have simple channelised approaches to separate points of conflict.

- The decision making for drivers is relatively simple. Drivers only look for traffic on the right, making it easier to judge an entry into the intersection.
- On undivided roads in high speed areas, long curvilinear splitter islands can provide good “advance warning” of the presence of the intersection and type of intersection.

These factors not only reduce the number of crashes but ensure that crashes are less severe than those that occur at other types of intersections. In this regard roundabouts fit well within the “Safe System” approach to road safety. The Safe System approach takes human errors and frailty into account, acknowledging that crashes will continue to occur but seeking to avoid death and serious injury as outcomes. Speed is a critical element in this approach. Speeds must be contained so that in the event of a crash the impact forces remain below human injury tolerance. Studies have consistently shown that the installation of roundabouts results in crash reductions of up to 75% in overall crashes and injury crashes (Austroads, 2013).

3. CAPACITY PERFORMANCE OF SIGNALS AND ROUNDABOUTS

The process of selecting an appropriate intersection control assumes that the preferred control is acceptable from a capacity point of view. **If an acceptable operational efficiency cannot be practically achieved for a particular type of intersection control, this would constitute a “fatal flaw”.** Operational performance is typically measured in terms of “Level of Service” and “Degree of Saturation”. Section 4.6.4 provides additional information on acceptable intersection operational performance based on these parameters.

3.1 Accuracy of Current Analytical Tools

The computer software SIDRA INTERSECTION has traditionally been used as the primary tool to analyse the capacity and operating performance of traffic signals, roundabouts and other non-signalised intersections in WA. More recently, Main Roads has started using LINSIG as an analysis and optimisation tool, particularly for signalised intersections, arterial routes and networks. The strength of LINSIG is as an optimisation tool for signalised intersections, so at this stage it is unsure whether it would be a preferred tool for roundabout analysis.

Although early manual analysis methods based on ARRB Research reports or Austroads guides are available, the SIDRA INTERSECTION software has refined these methods and theory over the years. While the roundabout analysis method used in SIDRA INTERSECTION was originally based on the Austroads Roundabout Guide, significant enhancements have been introduced in various versions of the program including the ability to analyse roundabout metering applications.

The current version of the software, SIDRA INTERSECTION 6, has the capability of analysing a road network comprising up to 20 intersections, whereas previous versions were only able to analyse individual intersections. This has enabled the analysis of linked intersections, such as a freeway diamond interchange, to be modelled more accurately.

Case studies relating to the validation of the SIDRA modelling are referred to in the SIDRA INTERSECTION User Guide. For signalised intersections, one case study indicates that performance measures for actuated signals were found to be highly accurate based on the results of real life surveys. In a roundabout case study, the analyses showed that the roundabout operated in excess of expectations in spite of increased levels of demand.

Micro-simulation software such as VISSIM and PARAMICS are also used to analyse roundabouts and traffic signals. The strength of these tools lies in their ability model networks taking into consideration the interaction between intersections as well as using an input flow profile over a period of time, rather than just for a peak hour. The graphic output is also very useful for demonstrating to stakeholders the impact of various options, in particular the impact on congestion and queue lengths. However, it should be borne in mind that these micro-simulation tools are a lot more time consuming and costly and should generally only be used if a demonstration is needed for community consultation or other stakeholder purposes at the end of the project.

3.2 Reliability of Capacity Analyses

The modelling of intersection capacity needs to consider a number of parameters including traffic volumes for the various movements, number of lanes and lane configuration, type of control, signal phasing, etc. The studies referred to in Section 3.1 and other anecdotal experience indicate that generally there can be confidence in the capacity analysis tools available. However, the results obtained from analysis may sometimes be questionable due to the following factors:

- Knowledge and expertise relating to the use of the software. Although the SIDRA INTERSECTION and LINSIG softwares are relatively user friendly, there are a number of variables to be entered and default values may need to be adjusted to accurately calibrate the program. All models of existing intersections should be calibrated based on field observations such as queue lengths, lane usage, saturation flow rates, gap acceptance and follow-up headways. Training and knowledge in the use of SIDRA INTERSECTION and LINSIG is essential.
- Knowledge and experience of the person undertaking the analysis relating to geometric intersection layout and parameters affecting capacity. The capacity analysis is closely related to the geometry of an intersection, the number of lanes, need for exclusive lanes and, if a signalised intersection, the type of signal phasing to be provided. Knowledge of these factors, as well as a sound knowledge of the SCATS operating system, is essential to the effective use of the capacity analysis computer software.
- Severely congested intersections may result in inconsistent performance outputs. In some situations the computer programs may also indicate uncertainty due to the analysis having ‘unsettled results.’ It is important that the designs have sufficient residual capacity to avoid these effects (refer to Section 4.6.4).
- The traffic volumes used in a capacity analysis are often the ‘weak link’ in the overall process of determining performance. This may be due to:
 - Using existing traffic counts where demand is much higher than the volumes able to clear the intersection. In this case existing throughput is counted rather than the volumes actually needing to use the intersection;
 - Adopting existing traffic volumes rather than future volumes based on an assessment of traffic growth. The determination of realistic design volumes is one of the keys to accurate modelling of intersection performance. This is discussed further in Section 5.6.3.

The actual performance of an intersection some years after construction may also lead to certain conclusions relating to the adequacy of the initial analysis or the form of control choice. For example, with traffic signals, the signal timings are only effective as long as the traffic patterns that were used to generate the initial signal timings or lane configurations remain reasonably similar. Over time traffic patterns change, so initial signal timings, phasing, linking plans or lane allocations should be reviewed to ensure effective operation. Similarly, traffic patterns may change at a roundabout and a review of exclusive lane allocation or need for change (additional lanes or metering signals) may be required. Ideally, flexibility should be built into an initial design, particularly in a developing area, to accommodate future changes.

Section 4.6.4 provides further discussion relating to capacity analysis of intersections and alternative forms of control involving roundabouts and traffic signals.

4. FACTORS AFFECTING THE CHOICE OF FORM OF CONTROL FOR ROUNDABOUT OR TRAFFIC SIGNAL INTERSECTIONS

4.1 Balancing the Factors to be Considered

Traffic signals or roundabouts are generally considered for major arterial road intersections with significant traffic flows where Stop signs, Give Way signs or other forms of channelisation would be unsatisfactory.

The objective when choosing a form of control for an intersection should be a cost effective control that balances the safety, operational and amenity needs of both motorised and non-motorised road users.

The choice of type of control of either a roundabout or traffic signal is influenced by consideration and 'balancing' of important drivers in the overall decision process. These may be either general factors relating to higher level objectives and viability or site specific requirements related to engineering and traffic operational details of the location involved. In the past there has been a focus primarily on the capacity analysis, or the operational performance of the intersection type. However, this should be viewed as only one factor, and ***provided that an acceptable operational performance is achievable*** (Section 3 refers), then the additional factors shown in Figure 4.1 need to be considered.

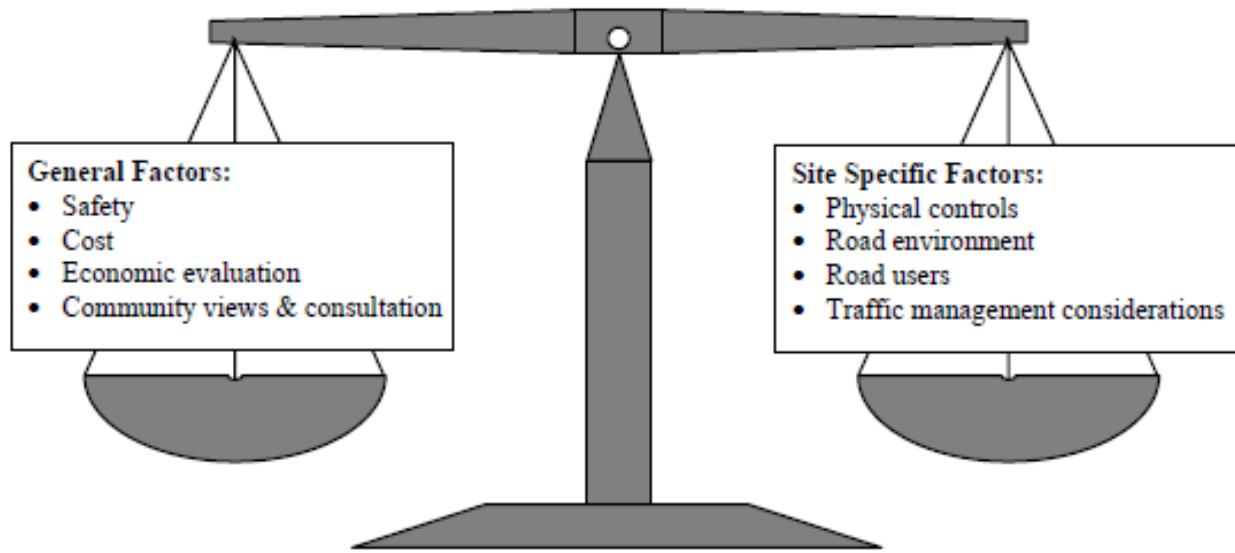


Figure 4.1: Balancing Factors in the Choice of Form of Intersection Control

The following Sections provide information relating to balancing these various factors. These are also summarised in Section 4.7.

4.2 General Factors

4.2.1. Safety

The safety of an intersection needs to be a key input when selecting a treatment or type of intersection control. Main Roads has adopted “The Road Towards Zero” Road Safety Strategy which aims to eliminate death and serious injury on the Western Australian road network. A key component of this strategy is the adoption of Safe System procedures, practices and programs. One of the cornerstone components of the Safe System approach is to reduce speeds at intersections so that any potential right-angle conflicts would be limited to a speed of 50 km/h. At that speed the likelihood of a motorist surviving a crash of this nature is 90%.

The research summary provided in Section 2 indicates that roundabouts are generally safer when compared with signalised intersections. Therefore, where signals are chosen at a site, it is generally accepted that there needs to be a balance between safety and other important factors at the site. To maximise safety on the road network, a roundabout would generally be the preferred option unless entry speeds can be reduced to 50 km/h or less, and unless other factors make a roundabout option inappropriate.

4.2.2. Costs

The initial cost of a control proposal may include:

- Land acquisition.
- Relocation of utilities.
- Construction costs.

The cost may also be influenced by the degree to which a proposal is to be compatible with staging of longer term works.

Recurrent costs may also need to be considered, particularly in relation to an economic evaluation. A form of control involving traffic signals would generally have higher recurrent costs than a roundabout. The costs include maintenance, linking and operation of the signals.

4.2.3. Economic Evaluation

The economic evaluation relating to a decision on control options under consideration needs to quantify and compare the anticipated benefits for each option (positive and negative) and costs discounted over the life of the control. The factors to be considered generally include:

- Safety performance - anticipated crashes that may occur (cost) or be saved relative to an alternative option (benefit).
- Capacity performance – delay costs or calculated delays relative to alternative options (cost / benefit).
- Initial cost.
- Recurrent costs.

The project life in the economic evaluation needs to consider a realistic timeframe relating to the nature of the works before the control may need to be replaced or upgraded. Common practice for assessment of ‘accident black-spot’ projects is to adopt a standard project life of 10 years for both signal projects and roundabouts. While the objective of the program is to address current crash problems, invariably the longer term capacity needs are not evaluated.

The project life can be an important issue in relation to capacity, particularly in a developing area where there is the potential for high traffic growth. Where forms of control are designed as a staging of medium or longer term works, a 20 year project life may be more appropriate. However, if a control is not compatible with upgrading to accommodate traffic increases, a shorter project life is appropriate. The travel time costs relating to operation would usually be based on calculated delays obtained from capacity analyses using design volumes for the peak periods. However, also considering the operation for control options during off peak operation provides a more precise assessment of 'whole of day' community benefits or disadvantages. The off peak operational periods during the day are particularly relevant for business and freight.

In determining the costs of crashes in WA, the Willingness To Pay approach has been used to estimate various crash type costs and severity costs. These are the average crash costs derived on the basis of the number of crashes of various types which occurred in WA over the five year period from 2009 to 2013 using the person costs the community is prepared to pay in order to eliminate a particular crash type. Table 4.1 gives the average severity crash costs by region.

| | Fatal | Hospital | Medical Treatment | Property Damage Only |
|---------------|-------------|-----------|-------------------|----------------------|
| Rural Regions | \$8,081,815 | \$476,035 | \$100,667 | \$11,651 |
| Metro Regions | \$7,116,751 | \$296,896 | \$73,469 | \$11,651 |
| WA Average | \$7,648,989 | \$351,226 | \$77,395 | \$11,651 |

SOURCE: (Main Roads WA, 2014)

Table 4.1: Average Crash Costs by Severity and Region in WA (2013 Dollars)

The information in Table 4.1 has been combined with the information in Table 2.1 to produce the average crash costs for signalised intersections and roundabouts in metro regions per million entering vehicles. These values, given in Table 4.2, may be used (suitably discounted, as applicable) in economic analyses. It should be noted that the significantly higher crash costs for signalised intersections is a reflection of the higher crash type severities.

| Mean Annual Crash Costs / Intersection / Year / 10 ⁶ entering vehs) | |
|--|-------------|
| Traffic Signals | Roundabouts |
| \$7,200 | \$4,000 |

Table 4.2: Mean Annual Crash Costs in Perth Metropolitan Area by Intersection Type (2013 Dollars)

4.2.4. Community Views and Consultation

The views of the Local Government Authority relating to community needs and preferences are key inputs to the decision making process. Inputs in relation to freight and public transport needs are also important. In some situations the views of the community or stakeholder groups (eg. a chamber of commerce or heavy vehicle operators) may also be desirable.

In some cases the community has a clear preference for roundabouts as they:

- Generally keep the traffic moving with minimal delay.
- Are more aesthetically pleasing than traffic signals.
- Are not traffic signals (Great Southern Region has resisted traffic signals for many years).

In other more developed or congested areas community groups (such as local cycling lobby groups) have indicated a preference for intersections controlled by traffic signals. A preference for traffic signals can be because they:

- Allow all traffic movements to get a turn in a signal cycle. This results in a form of control that is more predictable to use, often reducing stress on the user.
- Give pedestrians specific priority.
- Are safer for cyclists.
- Allow specific priority to public transport vehicles.
- Allow the use of longer delays for particular movements to discourage these specific movements.
- Traffic signalised intersections are generally smaller in area and have less impact on adjacent properties and services.

4.3 Physical Controls

4.3.1. Number of Intersection Legs and Angle between Legs

At intersections with more than four legs, if one or more legs cannot be closed or relocated, or some turns prohibited, roundabouts may provide a more convenient and effective treatment, since (a) with 'STOP' or 'GIVE WAY' signs, it is often not practical to define priorities adequately, and (b) signals may be less efficient due to the large number of phases required, resulting in a high proportion of lost time.

Single Lane Roundabouts

With single lane roundabouts, aligning roundabout legs at approximately 90° is preferable because it results in the least amount of driver confusion. This design limits the maximum number of roundabout legs to four. However, where economic and practical reasons have dictated, the provision of a greater number of legs on a single lane roundabout has proved workable in some cases. It is suggested however that more than six legs would lead to driver confusion as to which exit leg is required (Department of Main Roads, Queensland, 2006) as well as to confusion by entering drivers as to which exit circulating drivers are indicating to exit. Adequate signing may also be difficult to achieve.

It should also be noted that larger diameter roundabouts generally work better than smaller diameter roundabouts because the exits would be further apart. Moreover, if one or more of the exits are one-way only, this simplifies the layout and makes the driving task easier. However, very large diameter roundabouts can lead to higher circulatory speeds, which may create difficulties for entering vehicles, especially multi-combinational vehicles, to "pick the gap". It is important therefore that entering speeds are controlled by appropriate horizontal geometrics.

Figures A.1 and A.2 in Appendix A show examples of a five-legged and six-legged single lane roundabout in Queensland.

Multi-lane Roundabouts

Limiting the number of legs of a multi-lane roundabout to four and aligning them at approximately 90° is the most preferable treatment because drivers are easily able to comprehend the layout and determine the appropriate choice of lanes for their path through the roundabout. Multilane roundabouts with more than four legs have some or all legs aligned at angles other than 90°. On these roundabouts drivers can experience difficulty in determining which is the appropriate lane choice required for left, through and right turns on some of the approaches. In general, two-lane roundabouts with more than four legs may cause operational problems and should be avoided. However, the provision of a greater number of legs on a multilane roundabout has proved workable in a number of cases where some of the following conditions apply:

- One or more of the legs are one-way only.
- The roundabout has a large internal diameter and is an oval shape, allowing adjacent legs at each end of the oval to be at approximately 90° to each other.
- Some of the circulatory parts of the roundabout are single lane only.
- Lane allocations for downstream exits are clearly marked on the approaches to the roundabout through the use of pavement markings, overhead signage, or both.
- Effective use has been made of “spiral markings”. Commentary 1 provides guidance on the use of spiral markings.

Figures A.3 and A.4 in Appendix A provide examples of multi-lane roundabouts along the Pacific Motorway in Queensland with more than four legs each.

4.3.2. Number of Lanes through the Intersection

In WA there are currently no multi-lane roundabouts with more than two through lanes. Although the Road Traffic Code 2000 allows for more than two circulating lanes in a multi-lane roundabout there is a reluctance to implement such a configuration based on a perception of poor driver behaviour in two-lane roundabouts in WA.

Roundabouts with up to three circulating lanes have been successfully implemented in Victoria. Figure B.1 in Appendix B shows an example of a three-lane roundabout in a semi-urban environment. Figure B.2 shows an example of a 3-lane roundabout in a light industrial / commercial area. It should be noted that in both these examples, roundabout metering is applied during the peak periods.

4.3.3. Space Available

The Road Reserve width, size of intersection splays as well as the availability and/or cost of land acquisition are key considerations when choosing which form of control to adopt. The space needs to accommodate:

- The required number of traffic lanes to ensure appropriate capacity, including the provision of future left turn slip lanes in the ultimate stage, if required.
- The median width to accommodate turn pockets, roadside furniture such as signals and direction signs and to store crossing pedestrians safely.
- The turning paths for design vehicles at an appropriate radius.
- The clearances to the Road Reserve boundary for footway or verge areas.

For example, with reference to Figure 4.2, to accommodate a design semi-trailer turning right at the minimum inside radius of 10m, the carriageway width of the roundabout would need to be approximately 8m for a single lane roundabout, giving an inscribed circle radius of 19.75m. Allowing for 5.5m for Road Reserve clearance gives a total footprint roundabout diameter of 50.5m.

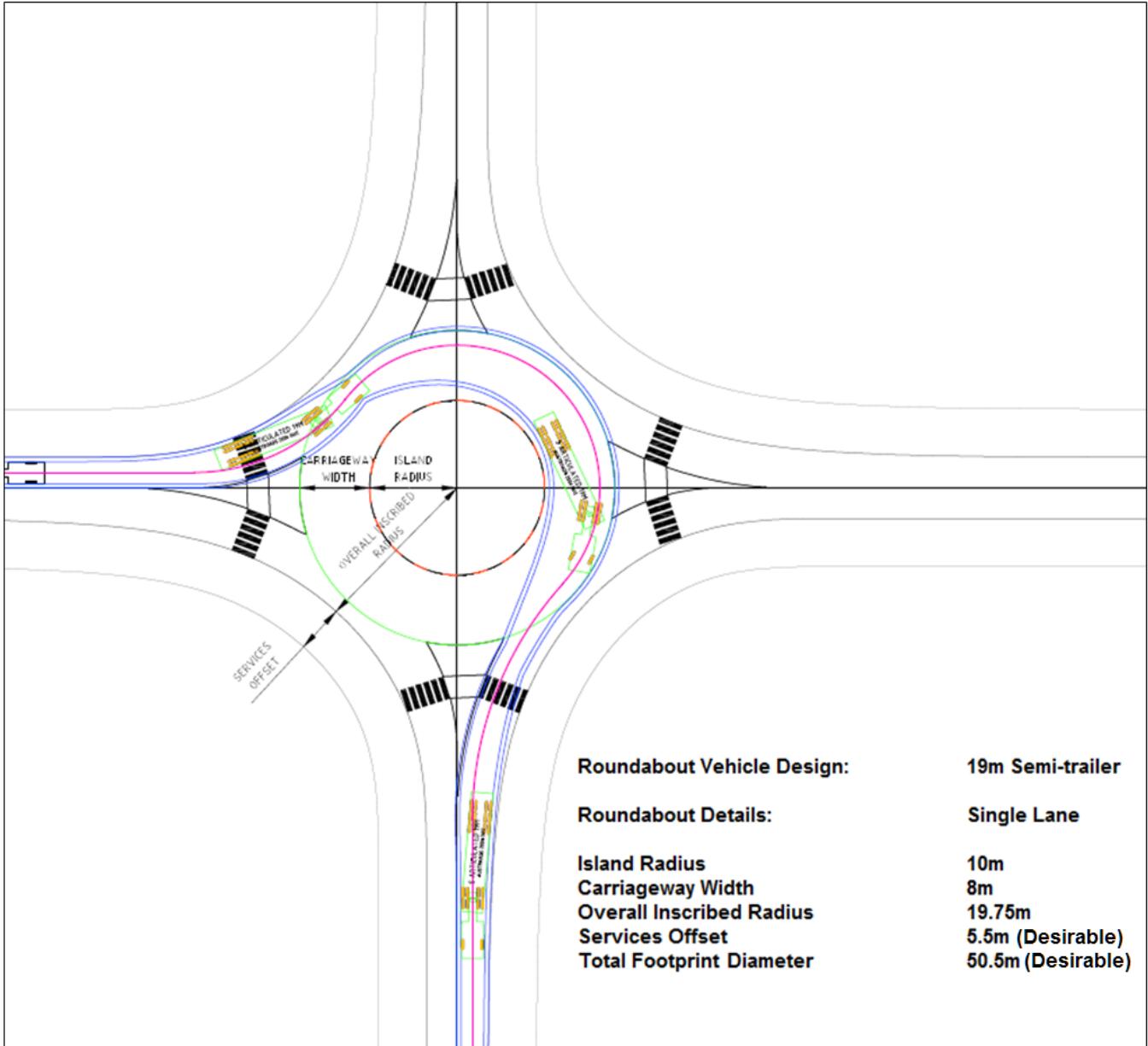


Figure 4.2: Space Requirements for a Single Lane Roundabout with 19m Semi-trailer as Design Vehicle

Similarly, for a two lane roundabout with the same design vehicle, the carriageway width would need to be approximately 18m, giving an inscribed circle radius of 30m. Again, allowing for 5.5m for Road Reserve clearance gives a total footprint roundabout diameter of 71m. Table 4.1 gives the space requirements for single and two lane roundabouts for a range of standard design vehicles.

| Vehicle Type | Minimum Island radius (m) | | Carriageway Width (m) | | Overall Inscribed Radius (m) | | Total Footprint - Desirable Diameter ¹ (m) | |
|------------------|---------------------------|------|-----------------------|------|------------------------------|------|---|------|
| | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| 19m Semi-trailer | 10 | 18 | 8 | 9.7 | 19.75 | 30 | 50.5 | 71 |
| 36.5m A-Double | 12 | 26 | 9.9 | 10.6 | 24 | 38.6 | 59 | 88.2 |
| 53.5m A-Triple | 20 | 30 | 10.1 | 11.6 | 31 | 43.5 | 73 | 98 |

1. Assuming a 5.5m verge width to Road Reserve boundary.

Table 4.1: Space Requirements for Roundabouts

When planning new areas for future development, the Road Reserve widths and splays can enable flexibility for future control options.

4.3.4. Site Topography

The topography at a site can influence a designer's ability to achieve appropriate standards for sight distance, grades and crossfalls within the intersection. Crossfalls and grades need to be maintained within limits to provide stability for turning vehicles with a high centre of gravity. This requires relatively level ground unless significant earthworks are undertaken which will also have an impact on the cost of construction.

Ideally, roundabouts should be sited on relatively level ground or in sag vertical curves rather than near crests, so that road users have good visibility and can adjust their driving behaviour to reflect the layout. In addition, relatively flat grades on intersection approaches facilitate acceleration of heavy vehicles and acceptance of gaps by drivers.

4.3.5. Access to Adjacent Properties

In some locations the nature of access to adjacent properties may need to be considered where major points of access and turning movements to private property occur at or close to the intersection. Roundabouts facilitate opportunities for improvement access management on arterial roads by enabling vehicles to access nearby properties through a left-in, left-out manoeuvre (see Figure 4.3). This can avoid the need to implement median breaks within a turn pocket.

However, it should be noted that access to adjacent properties needs to be carefully managed and controlled in accordance with the Main Roads' Driveways Policy. On regional roads the practice should be to limit and control property access to provide both traffic safety and efficiency benefits.

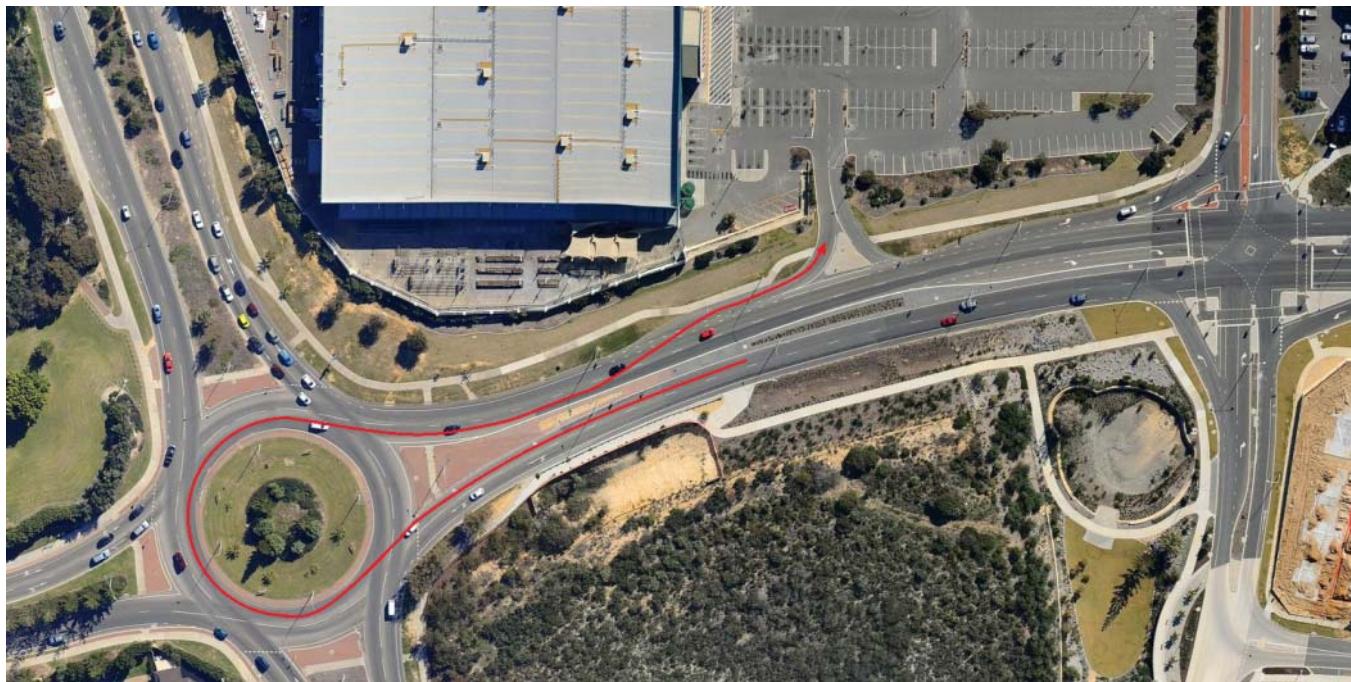


Figure 4.3: Example of left-in, left-out access near a roundabout

4.4 Road Environment

4.4.1. Rural, Outer Urban and Inner Urban Areas

In all areas both signalised intersections and roundabouts should have lighting. ([Click here for a link to the Lighting Guidelines](#)) In addition, where the approach road is speed zoned at 90 km/h or above, the approach shall be a speed zone not greater than 80 km/h with a desirable length of 500m and a minimum length of 300 metres. On divided carriageways, if offset speed zones are appropriate, the length of the speed zone should be reduced to 100 metres on the departure side of the road feature. ([Click here for a link to the Speed Zoning Guidelines](#)).

In rural areas traffic signals would generally be inappropriate due to the nature of the road environment, relatively low traffic volumes and the approach speeds of traffic. Roundabouts should be considered where a T intersection, staggered T intersection, or wide median control would be unsatisfactory due to the relative traffic volumes involved. They are also appropriate at rural cross intersections (including those in high speed areas) where there is a crash problem involving crossing or right turn (vs. opposing) traffic. However if the traffic flow on the lower volume road is less than 200 vehicles per day, consideration should be given to using a staggered treatment. Studies have indicated that the crash reduction achieved by roundabout installation in high speed areas has been similar to that for low speed areas. (Austroads, 1993). Moreover, the study showed that there were no casualty crashes in the three years following the installation of roundabouts in the high speed areas, indicating the reduced severity of crash types as a result of the roundabout installation.

Roundabouts in rural, high speed environments must be highly visible and incorporate appropriate geometric characteristics (deflection of approaches, central island size, long splitter islands etc), signs and pavement markings to ensure safe operation. In rural WA, particular emphasis needs to be placed on designing an intersection solution that meets the needs of multi-combinational vehicles (refer to Section 4.5.3).

In rural towns and cities with short peak periods, roundabouts would generally be appropriate and operate with minimal delays. Roundabouts also facilitate U-turning movements where traffic circulation in a shopping or town centre is a consideration. At cross or T intersections where the major flow of traffic turns right or left (which often occurs on highways in country towns) and at other Y or T junctions where a high proportion of right turning traffic exists, a roundabout will generally provide a safe and efficient form of control to manage the turning traffic. Traffic signals (or separate nearby pedestrian crossings or pedestrian signals) need to be considered in areas with high pedestrian numbers.

Roundabouts are also appropriate at arterial and collector roads in outer urban areas and country towns where only short periods of congestion occur. In such situations, control by traffic signals would be relatively inefficient and costly from a maintenance and operation point of view.

In outer urban and fringe areas either traffic signals or roundabouts may be appropriate, subject to other considerations described in this section. However, roundabouts would generally provide safety advantages and lower delays in off peak periods.

For inner urban areas roundabouts may be appropriate at sites which are not influenced by adjacent intersections and where space and other factors are appropriate. However, traffic signals are often the preferred form of control due to pedestrian or signal linking needs.

4.4.2. Speed of Approaching Traffic

In WA, where the approach road is speed zoned at 90 km/h and above, the approach to a signalised intersection or roundabout shall be a speed zone not greater than 80 km/h with a length not less than 300 metres before the intersection.

In high speed traffic environments, such as in rural or urban fringe areas, roundabouts generally operate safely and provide physical control of speed when designed with appropriate alignment and channelisation. This may be difficult to achieve where there are restrictive vertical and horizontal geometric issues.

If traffic signals are used in high speed areas, in addition to the mandatory 80km/h maximum speed zone, the use of advanced warning devices may also need to be considered. However, these measures generally have limited success in controlling speeds without regular enforcement or installation of a red light / speed camera.

In these environments, where capacity and other constraints such as land are not an issue, it is generally preferable to keep the traffic moving with roundabout forms of control, rather than using traffic signals.

4.4.3. Adjacent Land Use

Traffic signals or roundabouts may operate satisfactorily in a range of environments. However, the nature of the adjacent land use may influence a decision.

At strip shopping centres in urban areas and rural townships, roundabouts at each end of the shopping area can be advantageous in slowing traffic entering the area and in providing U-turn opportunities for motorists circulating to and from kerbside parking.

In an industrial area where a median may restrict vehicle movements into adjacent properties, a roundabout of appropriate size may also facilitate circulation and U-turning of trucks. The special needs of multi-combination vehicles may preclude this option. Moreover, if towed agricultural implements and /or over dimensional loads being transported on oversize trailers (with very wide wheel spreads) are required to operate out of the industrial area this should be taken into account.

4.5 Road Users

4.5.1. Needs related to Pedestrians

Pedestrians are unprotected road users and therefore are generally at greater risk than road users in motor vehicles. Pedestrian needs on the road relate to mobility and safety and this is of particular concern in relation to children, the elderly and people with disabilities.

In high traffic volume locations, pedestrians generally prefer to use traffic signals as these provide priority with a pedestrian signal phase and separation from through traffic flows. Pedestrian crashes at signalised intersections generally involve turning traffic failing to give way, pedestrians crossing against the red light or vehicles driving through the red light.

While crash data at roundabouts generally indicates that there is not a particular safety problem for pedestrians (refer Section 2.3), there is a general dislike for roundabouts by pedestrians and a perceived safety risk as they may be difficult to cross. Pedestrian concerns at roundabouts generally relate to:

- No specific priority for pedestrians compared to signals where 'Walk' phases are provided.
- Drivers looking right towards circulating or entering traffic, rather than watching for pedestrians.

Pedestrians crossing from the left may be more vulnerable in this situation.

- Lack of gaps in the traffic flow, particularly at congested roundabouts and moving queues of traffic, rather than the queue of vehicles coming to a complete stop.
- Roundabouts with two or three lane approaches presenting greater crossing difficulties for pedestrians compared with single lane roundabouts, even with the provision of splitter islands which can act as staging points.
- The long walking distances involved in negotiating a large roundabout may be a concern to some pedestrians.

4.5.2. Provision for Pedestrians at Roundabouts

Where a roundabout is being considered in an environment with pedestrians, consideration should be given to incorporating the following design features, as appropriate, and in accordance with design guidelines:

- Pedestrian signals across the approaches - to provide for children, elderly persons or pedestrians with disabilities.
- Pedestrian (zebra) crossings or pedestrian signals across approaches – where a significant number of other pedestrians are expected (e.g. near a shopping centre or school).
- A lower design speed than usual, generally 40 km/h maximum (usual maximum is 50 km/h), to slow vehicles entering and travelling through the roundabout. This will improve the ability of pedestrians to cross and also assist in reducing the severity of injury in the event of a pedestrian crash.

This lower design speed is achieved with physical horizontal deflection of vehicle paths prior to the pedestrian crossing points using an appropriate left hand curve radius and a splitter island or shaping of the median. The size of the central island and the adverse crossfall of the circulating roadway also assist in controlling vehicle speeds. Tighter geometry to achieve low exit speeds, rather than the usual practice of facilitating the exiting of vehicles, will also improve safety for pedestrians crossing the roundabout departures.

- Ensuring good visibility so that pedestrians can see traffic and be seen by drivers and motorcyclists.
- Ensuring the roundabout has adequate vehicular capacity. With minimal congestion, the resultant gaps in traffic flow can facilitate pedestrians crossing the vehicle flows on approaches and departures (Note: pedestrian needs are usually considered in traffic signal capacity analysis but rarely considered in relation to roundabouts).
- Pedestrian crossing points set back approximately 6 metres or 12 metres (one or two car lengths) from the holding line to separate the points where pedestrians and circulating vehicles cross a driver's path. At this location a pedestrian is not crossing in front of vehicles about to enter or leave the circulating roadway and is more likely to be seen by a motorist in the queue. (Balance must be made here as vehicles exiting the roundabout will be accelerating as they pass this point and drivers coming out of the roundabout may not see pedestrians using the crossing).
- Splitter islands on each leg of the roundabout being of sufficient size to provide staging points for pedestrians (including wheelchairs, bicycles, prams etc.). This enables pedestrians to cross one direction of traffic flow at a time and also minimises the width of roadway to be crossed.
- Where a signalised pedestrian crossing is provided across an approach, the crossing points across each section of roadway should be staggered at the median or splitter island to minimise 'walk' times and delays to traffic. The stagger also increases the distance for queuing on the departure before traffic interferes with the circulating flow in the roundabout. Section 7.1.2 provides more information on the use of signalised pedestrian crossings at roundabouts.
- Consideration of fencing or landscaping to discourage inappropriate pedestrian movements and to direct pedestrians to the formal crossing points.

4.5.3. Needs related to Cyclists

Crash data (Austroads, 1999) generally indicates that there is a safety problem for cyclists at roundabouts. Cyclists are unprotected road users at greater risk than motorised road users. Therefore, where there is a high speed differential between bicycles and other vehicles, designs need to minimise risks to cyclists either by regulating the speeds on the approach and circulatory roadway through appropriate geometrics or by providing a separate off-road space.

At traffic signals a cyclist's mobility needs relate primarily to sharing road space.

At roundabouts, cyclists' concerns relate more to safety and operation such as:

- Motor vehicles travelling too fast.
- Motor vehicle drivers failing to see circulating cyclists and consequently entering the roundabout and in the process not giving way to cyclists in the circulating roadway. This may because cyclists tend to "hug" the left-hand side, especially on multi-lane and wider circulatory roadways where there is sufficient space for cars to pass. It may also be because cyclists, due to their smaller presence, are not as visible as cars.
- Motor vehicles cutting across lane lines.
- Cyclists needing to cross the path of exiting vehicles, particularly at multilane roundabouts.

Conventional right turning manoeuvres at multi-lane roundabouts are a problem for cyclists because of the nature of their interaction with motorised traffic. In terms of the Road Traffic Code 2000, cyclists may undertake a hooked right turn. This means that cyclists must give way to traffic exiting the roundabout and therefore provision of a storage area (i.e. a refuge) may be considered on the left side of exits where cyclists can wait for a gap in the traffic.

Cyclists differ from drivers in that they have a broad range of age and ability and have to be able to balance the vehicle whilst negotiating the road and traffic situations. The type of cyclist to be catered for is an important design consideration. The main types of cyclist using the road system are recreational cyclists and commuter cyclists, although regular recreational cyclists may have similar characteristics and needs as commuter cyclists.

Recreational cyclists:

- Generally ride for the enjoyment of the ride and companionship
- Are more likely to be inexperienced
- Are not intent on getting to a destination as quickly as possible
- Often prefer not to ride on the road

On the other hand, commuter cyclists:

- Ride for transport to work or other destinations
- Are usually very experienced
- Often travel relatively long distances
- Choose to ride on the major roads because the trip length and travel time is less than on alternative routes, including paths

Many commuter cyclists are not attracted to off-road paths because:

- Paths are often indirect and not located to satisfactorily serve the commuter trip
- The path surface may not be as smooth as arterial roads, especially if the paths are constructed from concrete
- They have to give way and are exposed to risk at every intersecting road

- They perceive that there is a high level of conflict with other path users (e.g. pedestrians, pedestrians walking dogs, vehicles using driveways.)

Many commuter cyclists would consider that the use of an off-road path around a roundabout is unacceptable in terms of delay and risk (i.e. crossing the approaches and re-joining the traffic stream). It is in this context that commuter cyclists prefer to use the road network and it is therefore necessary to cater for cyclists at all intersections, including roundabouts. In these circumstances it is essential that the speed differential between motor vehicles and bicycles is minimised through appropriate speed reduction geometrics.

At roundabouts, although commuter or experienced cyclists would generally prefer to use the roadway and ride through a roundabout with the traffic, an option to leave the road and use an off-road shared path is preferable, particularly for inexperienced cyclists and children. Even with uncontrolled pedestrian / cyclist movement across each approach leg, there is some evidence to suggest that this is the safest design, at least when traffic flows are high (Austroads, 2013).

In an area with significant bicycle usage (particularly children or recreational cyclists), preference may need to be given to traffic signal forms of control with specific provisions such as bicycle lanes, advanced stop lines and storage areas.

4.5.4. Provision for Cyclists at Roundabouts

Where bicycles are expected to use a site where a roundabout is the preferred form of control, specific provisions may need to be considered such as:

- Low design speed (generally 30 to 40 km/h) using horizontal curves (pre-deflection) to slow vehicles entering and travelling through the roundabout. This will enable cyclists to mix with other traffic and take control of the lane. This may also need to include a low exit speed incorporating tighter geometry than the usual practice of enabling vehicles to exit easily.
- Avoiding squeeze points for cyclists on the approach and through the roundabout. If a bicycle lane is provided on the approach it should be terminated before the holding line. At multi-lane roundabouts the bicycle lane should be terminated in advance of the intersection by the provision of an off-ramp to a Dual Use Path or similar.. The provision of a separate channelised entry into the roundabout on the left of the general traffic lane is not recommended, as the separation of entering bicycles may not be obvious to motorists.
- Provision for cyclists to move off the carriageway to use shared paths around the outside of the roundabout, particularly at locations used by children or recreational cyclists. The crossings of the splitter islands should be wide enough to shelter a bicycle, be flush with the road pavement and be set back 6 metres, or preferably 12 metres (one or two car lengths), from the holding line. Pedestrian signals or a pedestrian crossing (with or without flashing lights) could also be considered (refer Section 4.5.2).
- At roundabouts used by cyclists or where a safety problem has developed, consideration should be given to the provision of signs and / or markings to warn motorists to look out for and give way to cyclists moving around the roundabout.
- Provision of a by-pass on three legged roundabouts for cyclists travelling along the top of the T-intersection.
- On approaches where the skew of an intersection necessitates provision of a left turn slip lane on the corner of a roundabout, a marked bicycle lane may be required.
- Provision of a marked bicycle lane where a major vehicle movement is able to by-pass a roundabout at speed.
- Where a bicycle path or shared path is provided around a roundabout, the intersection between the path and road should be designed to ensure that cyclists are able to safely cross the road and

- enter the bicycle lanes that may exist on the roundabout approaches and departures.
- It should be noted that it is not Main Roads' practice to install on-road cycle lanes within the circulating carriageway. (It should be noted that Austroads GRD Part 4B: Roundabouts is currently being modified to exclude on-road cycle lanes in roundabouts).

4.5.5. Needs of Large Vehicles

Signalised intersections are considered to provide a more convenient treatment for the drivers of large trucks than roundabouts, depending on the characteristics of the particular intersection. While trucks at times will encounter the inconvenience of coming to a complete stop at a red signal, they are often able to continue through a green signal. This is generally preferred to the inconvenience associated with negotiating a roundabout (Austroads, 2013) where multi-combinational vehicles struggle to "pick a gap" when the circulatory traffic is high due to poor acceleration characteristics. However, it should be noted that at signalised intersections the traffic signal timing needs to accommodate the heavy vehicle acceleration characteristics. Moreover, traffic lights on downgrades are a problem for heavy vehicles and Advance Warning Flashing Signs are essential when traffic lights are on a downgrade.

In rural and semi-rural environments, the drivers of large vehicles dislike slowing down for a roundabout. In Victoria, in instances where the freight industry has indicated concerns after roundabouts have been installed at an intersection, the context of comments has generally been related to the previous intersection layout where traffic on the major road had right-of way and there was no need to slow down. However, the roundabouts at these locations had generally been installed for safety reasons or to enable vehicles to enter the major road from the intersecting arterial. Traffic signals in these locations would require traffic to slow and/or stop and this may have greater impact on freight movements. Generally, in these rural or semi-rural environments, it is preferable to keep the traffic moving with roundabout, Give Way or Stop controls, rather than using traffic signals. Give Way and Stop controls are applied to the minor intersection legs only resulting in negligible delay to the major through movements.

When considering heavy vehicles, particularly multi-combinational vehicles, the success of implementing a roundabout will be highly dependent on the truck driver's ability to pick a gap in the circulating traffic. This is greatly influenced by the circulating traffic volumes as well as the roundabout geometry; good sight distance is essential for truck drivers to be able to adjust their approach speeds to suit the gaps in the circulating traffic. This also highlights the importance that any capacity analysis makes suitable adjustments to the percentage heavy vehicles as well as gap acceptance parameters and follow-up headways for heavy vehicles.

A functional intersection layout based on the characteristics of a design vehicle should represent an economical level of design that caters safely, efficiently and comfortably for at least 85% of vehicles operating in accordance with normal traffic regulations, provided that on road train routes, the applicable multi-combinational vehicle (e.g. 53.5m triple road trains and 36m double road trains) should be selected as the design vehicle, in which case they should enter and depart from the intersection in the correct lane/s. However, where these vehicles and other vehicles operating under restricted access only use the intersection occasionally, it may be acceptable for the design to be based on them encroaching into the other traffic lanes. This may cause some inconvenience to other road users, but may be acceptable where there is a low frequency of occurrence together with the effect of special conditions associated with the permit.

For confined locations where a smaller roundabout needs to accommodate heavy vehicles, a heavy vehicle apron may be constructed around the central island to increase the circulating road width and facilitate right-turn movements. The heavy vehicle apron should be raised using mountable kerbing so as not to compromise the deflection path of standard vehicles proceeding straight through the roundabout (refer to Main Roads Roundabout Guidelines for heavy vehicle apron details). Main Roads

supports the use of raised encroachment areas around the central island for permit vehicles only. It should be noted that raised aprons are not desirable on roundabouts where it is used by trucks carrying animals or fuel trucks.



Figure 4.4: Example of a Heavy Vehicle Apron Around the Central Island of a Roundabout

It is also important that practitioners are aware, through traffic data or other local knowledge, whether the location is subjected to seasonal cartage where the number of large vehicles may be very high for a relatively short period of time (e.g. harvesting of crops). In such cases the typical seasonal cartage vehicle should be considered as the design vehicle.

Where the route is designated for the use of special vehicles that fall outside of the three general classes (other freight efficient vehicles, over-length buses, type 1 or 2 road trains), or where regular use of the route by these vehicles could reasonably be expected (access to industrial areas, bus routes), the design should satisfy the needs of such vehicles. The operation of these vehicles should not be compromised by having to encroach into other traffic lanes. In some cases roundabouts have been constructed to enable over-dimensional vehicles to drive straight through the central island (e.g. The new Boud Avenue dog-bone interchange on Tonkin Hwy, which is still under construction).

In inner and outer urban areas, for the geometric design of intersections, the 19m Semi-trailer is typically used as the design vehicle for cross section elements and turning paths and the Car is used as the design vehicle for horizontal and vertical geometry. The geometric design should also be checked for other design vehicles (such as B-Doubles, Road Trains or Tri-Drives) where they are likely to be permitted or encountered.

In rural areas intersections on major roads and highways should be designed to cater for a 36.5m A-double road train as a minimum. The design should also cater for 53.5m A-triple road trains if the Main

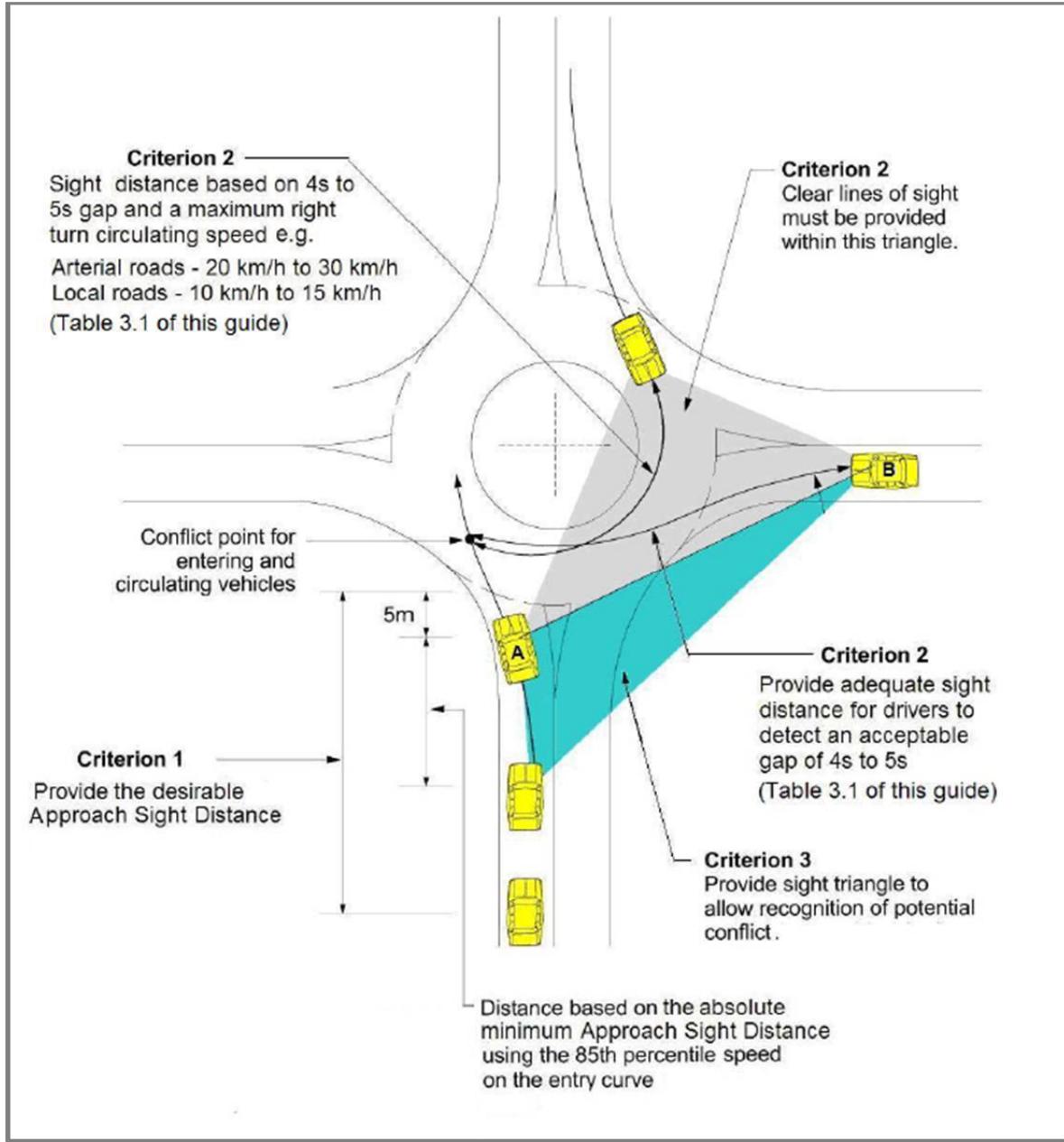
Road's Region permits use of these vehicles. Designers should refer to the RAV Network for further information and should confirm whether there are any planned expansions of the network in the near to medium future (10 years).

4.5.6. Provision for Large Vehicles at Roundabouts

Where large or special vehicles are expected to use a site where a roundabout is the preferred form of control it is important to:

- Provide appropriate space for the swept path of large vehicles such as semi-trailers and buses (refer to Section 4.3.3).
- Provide truck stopping sight distance
 - understanding that lateral sight distance restrictions are often critical, particularly at T-junctions in hilly terrain and near bridge piers.
 - understanding that at roundabouts it is difficult for drivers of multi-combinational vehicles to “pick a gap” – consequently it is important that if the design vehicle is an A-double, or larger, all three sight distance criteria given in the Austroads Roundabout Guidelines (Austroads, 2011) must be satisfied. If the design vehicle is a 19.0m semi-trailer, then only criteria 1 & 2 must be satisfied. The sight distance criteria are shown in Figure 4.5.
 - for intersections on or near crest vertical curves
 - to allow large / special vehicles to turn safely into each road
 - to railway crossings, speed change areas and merge areas such as lane drops
- Consider vehicle stability for turning movements by providing radii appropriate for the turning speeds and providing a satisfactory crossfall and a uniform rate of change of crossfall. This is particularly important for multi-combinational vehicles where the prime mover and trailer(s) may be on different crossfalls at the same time. Where possible, this needs to be minimised and should be checked using software such as HVE (Human, Vehicle, Environment) developed by Engineering Dynamics Corporation, USA, and used by Queensland Main Roads.

A case study example (Eelup Rotary in Bunbury) of designing a roundabout to accommodate multi-combinational vehicles is given in Appendix C. It should be noted that due to the high volumes at this roundabout, it was necessary to fully signalise the roundabout.



SOURCE: (Austroads, 2011)

Figure 4.5: Sight Distance Criteria to be Satisfied for Multi-combinational Vehicles at Roundabouts

4.6 Traffic Management

4.6.1. Route or Area Strategies

The consideration of route strategies when selecting a form of intersection control includes consideration of the form of control at adjacent intersections. For example:

- Traffic signals would be appropriate where adjacent intersections are controlled by traffic signals and the spacing of intersections would enable effective signal linking. Roundabouts in this traffic environment would interfere with the platoons created by adjacent traffic signals and a conventional signalised (or unsignalised) at-grade intersection would generally provide a better level of service than a roundabout.
- Roundabouts would also be inappropriate where traffic flows leaving the roundabout would be interrupted by a downstream traffic control which could result in queuing back into the roundabout. An example of this is a nearby signalised pedestrian crossing. The use of roundabouts at these

sites need not be completely discounted, but they are generally found to be less effective than adopting a signalised intersection treatment.

- Roundabouts are more appropriate than traffic signals at relatively isolated locations or where the adjacent sites have roundabout control.

4.6.2. Road Hierarchy, Local Access and Amenity

Area strategies relating to the use of Local Government roads may also need to be considered. The functional road classification of the intersecting roads needs to be considered when determining the appropriateness of a form of control (refer to section 1.1). This could be an issue where control of traffic into a local area is important for amenity reasons. This may occur where a Local Government road intersects with an arterial road intersection and ‘rat running’ could occur. In these situations traffic signals would give greater control of traffic movements, in the same way traffic signals enable priority to be given to particular routes / turns which warrant priority movements.

4.6.3. Traffic Volumes and Traffic Signal Warrants

In choosing a form of control for an intersection, operational analyses require an understanding of traffic volumes and the mix of traffic (eg. percentage and types of heavy vehicles) that are to use the intersection during anticipated periods of peak flow.

The first step is to determine design traffic volumes that would be applicable for the morning peak, evening peak or high flow periods such as events, recreational periods, crop harvesting periods, holidays etc. The determination of design volumes may be based on:

- An existing turning movement traffic count. This may then be factored up using a growth rate appropriate to the site.
- Traffic studies considering a range of issues, including traffic growth that may result from development in the area or along a growth corridor.
- Network modelling that estimates future traffic flows. These may be based on various scenarios relating to land use development or road network improvements. In the Perth Metropolitan Area the ROM24 model may be used to estimate future peak hour traffic volumes and obtain projected turning movements at major intersections. It should be noted that any projected modelled volumes need to be adjusted based on a comparison between Base Year modelled volumes and actual count data for the same year.

In line with the economic evaluation, forecast traffic volumes should be based on a horizon year of at least 10 years after opening for both signal projects and roundabouts. However, where forms of control are designed as a staging of medium or longer term works, a 20 year project life may be more appropriate. However, if a control is not compatible with upgrading to accommodate traffic increases, a shorter project life is appropriate.

At locations where traffic growth is expected to be high and where future traffic patterns are uncertain or changeable, roundabouts may be appropriate. Care should be taken in assessing the future traffic volumes and their patterns. It is possible that a site considered appropriate for a roundabout now may become inappropriate in the future, requiring extensive modification to the intersection. Designers should consider the potential to build flexibility into the design to accommodate possible future changes, particularly when land use changes are likely to alter traffic patterns and volumes considerably.

It is important that traffic control signals are installed in situations where they are justified in order to be respected by the travelling public. Main Roads is in the process of developing a *Policy and Application*

Guidelines for Traffic Control Signals document, which will provide criteria for their installation based upon minimum traffic volumes, minimum spacing between successive signalised intersections and other factors to be used in conjunction with traffic analysis to ensure that traffic signal control is an appropriate form of treatment and that expected level-of-service and road safety outcomes are achieved.

4.6.4. Capacity Analysis

The capacity of a form of control to operate satisfactorily is dependent on the traffic volumes during periods of peak flow, including the volumes of turning traffic and the distribution of traffic on the various approach legs at the intersection. Therefore, it is important to determine appropriate design volumes as outlined above.

Analyses are best undertaken using software which provide the key output measures relating to operational performance for a proposed intersection layout of Level of Service (LOS), Degree of Saturation (DOS) and (in some situations) Length of Queues for evaluating or comparing performance of individual lanes, approaches or the intersection as a whole.

Level of Service (LOS)

The Level of Service (LOS) measure for intersections is “control delay” (measured in seconds) and is a measure of the driver discomfort, frustration, fuel consumption and increased travel time. As control delay increases, LOS worsens. LOS for intersections, based on the *Highway Capacity Manual 2010* is given in Table 4.2 below:

| Level of Service | Control delay per vehicle in seconds (d) (including geometric delay) | |
|------------------|---|---|
| | Signalised Intersections | Priority Controlled Intersections and Roundabouts |
| A | $d \leq 10$ | $d \leq 10$ |
| B | $10 < d < 20$ | $10 < d < 15$ |
| C | $20 < d < 35$ | $15 < d < 25$ |
| D | $35 < d < 55$ | $25 < d < 35$ |
| E | $55 < d \leq 80$ | $35 < d \leq 50$ |
| F | $d > 80$ | $d > 50$ |

Source: (Transportation Research Board, 2010)

Table 4.2: Level of Service Definitions based on delay (HCM Method)

It should be noted that the delay for a particular level of service at signalised intersections is higher than the delay for the corresponding level of service at a priority controlled intersection or roundabout. This is because drivers tend to expect (and tolerate) higher delays at signalised intersections compared with non-signalised intersections. Analysts need to be aware of this when comparing results using packages that only report the intersection delay, and not the level of service as defined in Table 4.2.

Degree of Saturation (DOS)

The Degree of Saturation (DOS) is defined as the ratio of *demand flow to capacity* (also known as the volume to capacity ratio – *v/c ratio*) for any particular lane. The movement DOS is the largest DOS for any lane of the movement. The approach DOS is the largest v/c value for any movement (or lane) in the approach and the intersection DOS is the largest v/c value for any approach.

Length of Queues

This is of particular importance in assessing requirements for the length of auxiliary through lanes or storage in turn lanes. The 95% queue length is generally adopted as the minimum storage for turn lanes, however longer lane lengths may be required for deceleration of vehicles.

Performance Criteria

For new (Greenfield sites) intersections, the following performance criteria should apply to the analysis based on traffic volumes in the target year (refer to Section 4.6.3):

The overall LOS for intersections during peak periods should be Level "C" or higher, with no individual major movement having a LOS lower than Level "D" and no individual minor movement having a LOS lower than Level "E". Moreover, no individual movement should have a DOS greater than the following:

- Signalised intersections 0.90
- Roundabouts 0.85

For existing (Brownfield sites) intersections, the following performance criteria should apply to the analysis based on traffic volumes in the target year (refer to Section 4.6.3):

The overall LOS during peak periods must be the maximum achievable using the lane configuration provided by the Project Manager in conjunction with the Asset Owner and no individual movement should have a DOS greater than the following:

- Signalised intersections 0.90
- Roundabouts 0.85

A sensitivity analysis to consider the implications of higher volumes may need to be considered where there is uncertainty regarding design volumes or future traffic growth.

Software Calibration

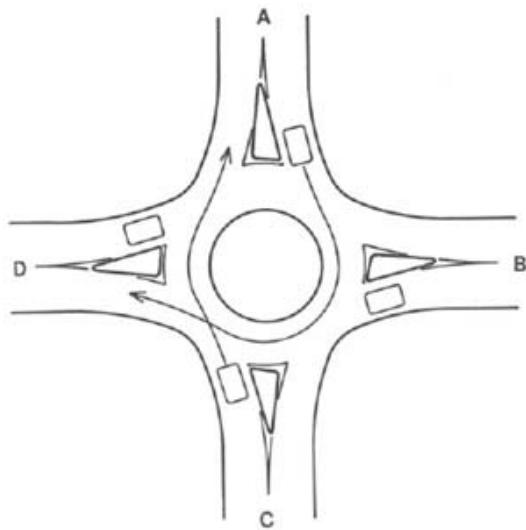
The calibration of the software for the capacity analysis is desirable when modelling congested intersections or comparing improvement options with an existing situation. The most critical 'default' values and parameters that can be modified when calibrating the software are:

- Lane saturation flows.
- Gap acceptance and follow-up headway parameters (these are particularly critical when assessing roundabouts with high percentages of multi-combinational vehicles: it is important that the analysis realistically reflects their reduced ability to "pick a gap").
- Phase and cycle times if signals are in a linked system (consultation with the Traffic Operations Centre is important to establish appropriate phasing and cycle times).
- Lane utilisation factor, where applicable.

A roundabout operating within design volumes will manage peak traffic flows in a self-regulating manner and provide acceptable delays under usual roundabout priority control. Even with relatively high traffic flows on each approach, traffic is generally broken up to create gaps in the circulating flow for entering traffic.

For multilane roundabouts, the provision of exclusive lanes for turning traffic is generally unnecessary unless a turning movement requires more than one lane. The shared lanes then provide more flexibility for off peak periods or times when flows vary from the design volumes used.

At intersections where there are high proportions of right turning traffic, roundabouts may be an appropriate form of intersection control. Unlike most other intersection treatments, roundabouts can operate efficiently with high volumes of right turning vehicles. However, satisfactory operation is dependent on the entering flows being balanced so that a heavy right turn does not cause excessive delays on subsequent entries. Right turning vehicles contribute to good roundabout operation because they create opportunities for vehicles on other approaches to enter the roundabout (refer to Figure 4.6).



In this example:

- 1 The right-turner from A to D would stop the through movement from C to A thus allowing traffic from D to enter.
- 2 Traffic from D would then stop the through movement from A to C thus allowing traffic from B to enter.
- 3 Right-turners from A in this example would initiate traffic flow on adjacent entries and D which would otherwise experience longer delay.

Source: (Austroads, 2013)

Figure 4.6: Effect of Turning Vehicles on Roundabout Operation

Where the entering traffic from a dominant leg prevents traffic from another approach from entering the roundabout (generally the adjacent approach to the left of the dominant flow), this deficiency can usually be addressed by the provision of part time metering signals that regulate the dominant flow and provide gaps in the circulating traffic. Metering signals are activated by queue loops in the approach that is being delayed. Further information relating to signals at roundabouts is provided in Section 7.

Roundabouts generally provide significant advantages over traffic signals in minimising delays during off peak periods. An economic evaluation may be based on calculated delays for the peak periods, but may also consider the operation during off peak operation. A 'whole of day' analysis provides a more precise assessment of benefits / disadvantages. Lower off peak delay during the day is particularly beneficial for business travel and freight.

At traffic signals, the number and layout of lanes and phasing are determined to suit peak demands. The phase times and operation for the varying periods through the day are then managed by the vehicle actuated controller and signal linking settings.

4.6.5. Project Life

Consideration of the project life can influence a decision on the form of control, particularly where significant future traffic growth may be expected. Consideration of the form of control compatibility with other future works is also an important input in the decision process. For example a single lane roundabout constructed as an initial form of control may be a staging of a multi-lane roundabout in the longer term. Alternatively, a roundabout may be chosen as an appropriate form of control to address current problems, even though traffic signals (or a signalised roundabout) may be envisaged in the long term. It is important that from a planning perspective that the ultimate configuration be superimposed to assess the potential land implications.

The project life needs to be consistent with adopted design traffic volumes and capacity analyses, as well as the value used for the economic evaluation.

4.6.6. Public Transport – Light Rail (Trams) or Buses

Traffic signals enable specific priority to be given to trams or buses through an intersection. Signals may also facilitate the clearing of queues at an intersection that may be obstructing the movement of a tram or bus. Traffic signals would generally be preferred where a tram service passes through a new intersection. However, tram routes have been successfully accommodated within roundabouts with satisfactory operation being supported by appropriate signs or signals.

In relation to buses, roundabouts generally provide lower delays during off peak periods and may also provide lower delays during the peak periods, subject to available capacity. Traffic signals provide greater control where bus priority or exclusive bus lanes are to be provided.

4.6.7. Public Transport – near Railway Level Crossings

The control of traffic movements adjacent to a railway level crossing can be a significant matter that affects the choice of the form of control to be adopted. Traffic queues extending across a railway level crossing are able to be controlled more effectively with traffic signals. These controls would generally include a ‘track clearance’ signal phase and ‘train’ phase within the cycle. A roundabout could be considered near a railway level crossing where traffic volumes are low or where capacity analyses confirm that queues will not extend across the tracks.

4.7 Summary of Site Specific Factors and Form of Control Choice

A summary of the various factors outlined in Sections 4.3 to 4.6 is provided in Table 4.3. This table is designed as a “quick reference” guide and should not be treated as definitive. For example any proposed signalised intersection in a rural area will be labelled as “unlikely” to be an appropriate type of treatment. This does not automatically preclude it as a possible treatment since most issues can be “engineered out”, albeit at a cost.

| Site Specific Factors | Signals | Roundabout |
|---|--|---|
| Physical Controls <ul style="list-style-type: none"> Number of intersection legs Number of through lanes Space available Site topography Access to adjacent properties | M – Up to maximum of 4 L – Up to 3 M – subject to design M – subject to design M – subject to design | M – Up to maximum of 6 L – Up to 2. M/U – Up to 3 – subject to design M/U – subject to design (may be difficult in Brownfield sites) M/U – subject to design (may be difficult in hilly terrains) M – subject to design |
| Road Environment <ul style="list-style-type: none"> Rural area Outer urban or fringe areas Inner urban area High speed approaching traffic | U M L M – May consider with 80 km/h speed limit & warning signs / flashing lights | L L M L - with design features to control approach speed |
| Road Users <ul style="list-style-type: none"> Pedestrian needs <ul style="list-style-type: none"> Children, the elderly and the disabled Significant number of other pedestrians Bicyclists needs <ul style="list-style-type: none"> Significant number of children or recreational cyclists Significant number of other cyclists Needs of large vehicles | L L L L L | U – unless pedestrian signals provided M - consider pedestrian facilities, low design speed and spare capacity U – unless off-road facility and pedestrian signals provided M – with low speed design M/U – may be difficult with high volumes & high % heavies |
| Traffic Management <ul style="list-style-type: none"> Route or area strategies <ul style="list-style-type: none"> Adjacent to linked signals Isolated locations Adjacent sites controlled with roundabouts Control of traffic through a local area Traffic volumes and capacity <ul style="list-style-type: none"> Balanced flows Unbalanced flows Significant turning volumes Minimising off-peak delays Public transport <ul style="list-style-type: none"> (Light Rail) Trams Buses Adjacent to a railway level crossing | L M M L M M M – with adequate turn lane capacity U L L L | U L L U M M – with metering signals L L U L U |

Legend:

L - Likely to be an appropriate form of control

M - May be an appropriate form of control

U – Unlikely to be an appropriate form of control

Table 4.3: Summary of Specific Factors and Form of Intersection Control Choice

5. USE OF TRAFFIC SIGNALS AND ROUNDABOUTS AT INTERCHANGES

To date in WA there has been limited use of roundabouts as junctions at service interchanges. However, with the increased “Safe System” approach to intersection design, it is recognised that roundabouts can offer significant safety advantages over signalised intersections. Commentary 2 (adopted from Austroads 2013) summarises the advantages and disadvantages of various types of service interchanges using either traffic signals or roundabouts as the form of intersection control.

6. TRAFFIC SIGNALS AT ROUNDABOUTS

Although the combination of traffic signals with roundabouts is not the main focus of this document, the following comments are provided in relation to the operation of traffic signals in conjunction with roundabouts.

In general, if appropriate intersection selection procedures are used, it will rarely be necessary to supplement a roundabout with traffic signals. However, if an existing roundabout is performing poorly in terms of delay on several approaches the benefits that might be derived from signalisation should be investigated through traffic analysis. Partial signalisation (i.e. metering of one or more entries) or full signalisation may be considered.

Moreover if the capacity analysis indicates that the residual capacity in the target horizon year is small (i.e. Degree of Saturation is close to 0.85) and there is a strong possibility of full signalisation being required, then the initial design should take into account the need to provide for internal queueing in the future (refer to Section 6.2) and the size of the roundabout should be designed accordingly. Also, any proposed change in intersection operational types should also check the suitability of the change for all expected vehicle operating characteristics.

The full signalisation of roundabouts can have a positive effect on some crash types (Dept. for Transport, April 2009):

- Crashes caused by poor judgement of gaps by drivers entering a high-speed flow of circulating traffic.
- Rear end crashes resulting from drivers having to simultaneously assess gaps in the circulating flow while watching the vehicle in front.
- Crashes with cyclists by regulating the speed of circulating traffic.
- Pedestrian crashes by providing protected crossings.

The partial signalisation of roundabouts (metering signals) can also have a positive effect due to increased capacity, although there may be a potential for increased rear-end crashes due to drivers becoming confused about two holding lines, (i.e. stop line at signals followed closely by holding line at roundabout entry). This may be mitigated by ensuring there is sufficient distance between the traffic signal stop line and the roundabout Give Way line. In addition, the use of two-aspect signals (red and amber) assists in preventing drivers from mistakenly driving through a green signal and failing to give way at the downstream give way line.

6.1 Partial Signalisation (Metering Signals) at Roundabouts

6.1.1. General Provisions

Roundabout performance is sensitive to unbalanced traffic flows. This may occur where the entering traffic from a dominant leg prevents traffic from the adjacent or another affected approach to the left of the dominant flow from entering the roundabout. This situation results in excessive queues and delays

on the affected approach.

The dominant traffic flow at a roundabout may be either:

- A high uninterrupted traffic flow.
- A low but consistent flow from a minor approach that takes priority over a major flow.

This deficiency can usually be addressed by the provision of part time metering signals that regulate the dominant flow and provide gaps in the circulating traffic. This enables the traffic from the affected approach to enter the roundabout. The metering signals are usually activated by queue loops in the affected approach that is being delayed, but may also be activated by downstream loops if a situation results in downstream traffic backing up into the roundabout. Metering can also be applied to more than one entry at a roundabout. Metering signals provide the following benefits:

- Management of the peak flows to provide appropriate priority for a major movement.
- Provide better balance of queues and delays between approaches.
- They can extend the life of a roundabout rather than require its replacement.

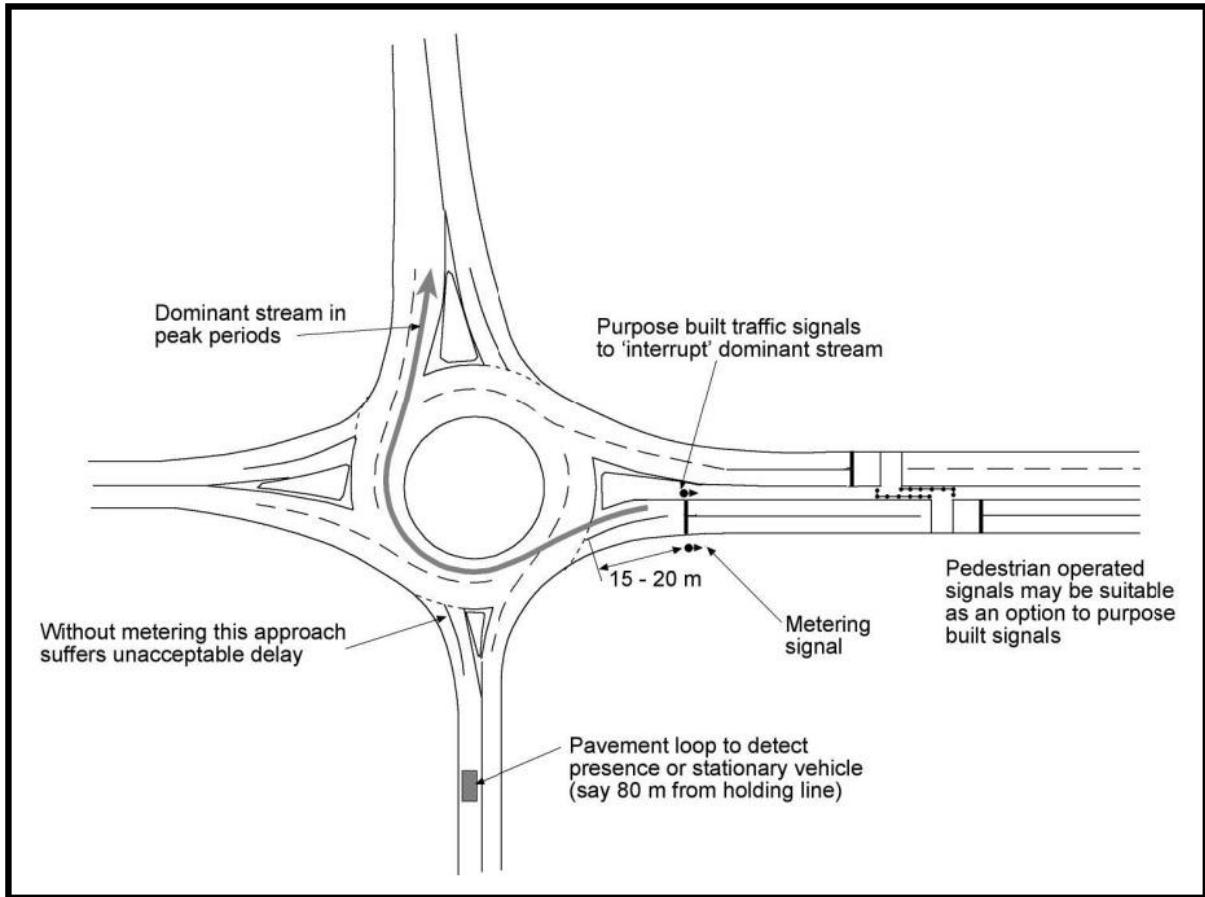
Metering signals are generally considered as a ‘short term fix’ stage when problems develop due to changing traffic flows over time. However, at some locations they could be considered as part of a new roundabout control to proactively manage the traffic. This form of control may avoid the need for installation of full traffic signals and retain safety and operational benefits at times of lower flow at the roundabout.

Metering signals use two aspect (yellow/red) lanterns set back on the approach to control the traffic. When traffic is released it enters the roundabout under usual ‘give way’ priority conditions in a self-regulating manner.

6.1.2. Provisions for Pedestrians at Roundabouts with Metering Signals

The provision of metering signals can also be beneficial for pedestrians, as the metering system can be combined with pedestrian signals to provide a pedestrian facility across a leg (or legs) of a roundabout. In these installations the signals would also stop traffic leaving the roundabout, so queuing of traffic may extend back into the circulating roadway. As the crossing distances and times are usually relatively short, this queuing is generally not a significant operational problem, depending on the frequency of operation. Subject to the pedestrian ‘desire line,’ at some sites it may be possible to locate the crossing further back from the circulating roadway so that storage on the roundabout exit is maximised.

Figure 6.1 illustrates metered roundabouts using purpose-built signals or pedestrian operated signals as an option. These facilities must be located with reference to the estimated traffic operation at the roundabout and potential pedestrian safety issues. It should be noted that in this case the pedestrian crossing is staggered so that any pedestrian negotiating the stagger faces the oncoming traffic. If the pedestrian crossing were to be located closer to the stop line, the stagger is reversed to give more storage to the exiting vehicles (refer to 2nd last dot point in Section 4.5.1 and Figure 6.2 for an example).



Source: (Austroads, 2013)

Figure 6.1: Metering of Roundabout Approaches

Where purpose built signals are used it is important that:

- They are located at least 15 to 20m in advance of the roundabout holding line to provide adequate separation between the roundabout regulatory signs and the traffic signals so that possible driver confusion is avoided.
- Signs (MR-GT-26) are provided at the signals to advise drivers that the signals are activated by traffic on other legs (the road name is usually specified).
- “STOP HERE ON RED SIGNAL” signs (R6-6) are provided.

Where pedestrian operated signals are used for metering:

- The crossing must be located a sufficient distance from the exit, and on divided roads pedestrian movements may have to be staged to ensure that traffic queues will not unduly affect the operation of the roundabout. Pedestrian desire lines and the provision of pedestrian fencing should be considered to encourage pedestrians to use the crossing.
- The crossing should be located a sufficient distance from the holding line and roundabout regulatory signs to avoid driver confusion (usually greater than that required for purpose built signals).
- Appropriate signage should be erected to inform drivers that the pedestrian signals may change for metering purposes (i.e. signals are not faulty).

Figure 6.2 shows an example of a metered approach using a pedestrian (pelican) crossing to control the traffic. It should be noted that the traffic signals facing the traffic approaching the roundabout may also be activated by traffic queuing on the controlling approach. However, the traffic signals facing the traffic

departing the roundabout will only be activated by a pedestrian waiting to cross the departing leg. It should also be noted that the stagger is reversed from Figure 6.1 in order to increase the stacking distance for vehicles departing the roundabout.



Figure 6.2: Example of a Metered Roundabout using Pedestrian Crossing Signals

As an alternative to providing pedestrian operated signals across both the approach and departure legs of a roundabout, consideration could also be given to providing pedestrian operated signals on the approach side and a zebra crossing on the departure side. An example of this in Melbourne is shown in Figure 6.3.



Figure 6.3: Roundabout Metering Using Pedestrian Operated Signals on Approach Leg only and Zebra Crossing on Exiting Leg

The main advantage of this approach is that the minimum red time is reduced because it is calculated on the width of one approach only and can reduce the delay to vehicles on the approaching leg. It should be noted that loops are also provided on the controlling approach to activate the signals during peak periods when no pedestrians are present.

6.1.2. Warrants for Roundabout Metering Signals

Currently, there is only one roundabout with metering signals in WA (see Appendix D). There was an initial concern that the part-time operation of the signals (generally only required during peak periods) may lead to driver confusion and error. Video surveys have highlighted some driver confusion and non-compliance but with few negative consequences.

However, when the ongoing increased maintenance costs for the traffic signals are added in, the installation of roundabout metering signals should not be considered as the first option. There are a number of means of improving the performance of the roundabout that should be considered first, before considering installing roundabout metering signals (Austroads, 1993):

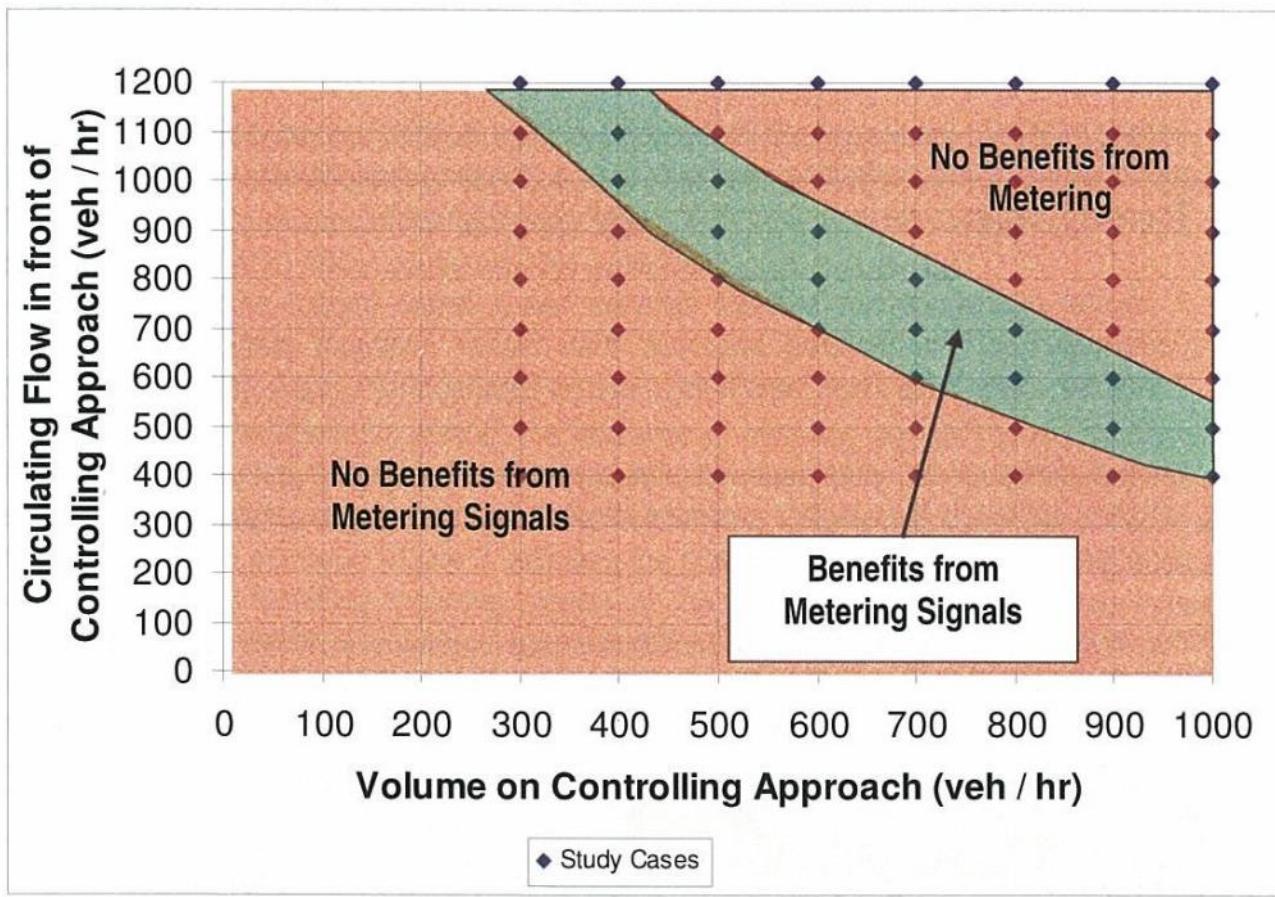
- Addition of continuous (left-turn slip) lanes
- Flaring (tapering) of the entries
- Adjustments to signal timings on adjacent intersections
- Signalised Pelican.
- Lighting.
- Implementation of ITS measures such as VMS and ESLS.

Main Roads has developed [Guidelines for the Analysis of Roundabout Metering Signals](#) in order to provide a consistent methodology to justify the installation of roundabout metering signals. More detail is provided on the implementation of the above treatments.

In addition, the guidelines cite a methodology for single lane roundabouts that compares the volume on the controlling approach with the circulating flow in front of the controlling approach to check whether there would be any benefit from installing metering signals (Natalizio, 2005). This is illustrated in Figure 6.4 and described below from the same source:

The results indicate that metering signals are required at a single lane roundabout when the combined volumes of traffic flow on the delayed (controlling) approach together with the circulating flow in front of the delayed (controlling) approach is between 1300 and 1400 vehicles per hour. The benefits of metering signals begin to decline once the combined volumes of traffic flow on the delayed (controlling) approach together with the circulating flow in front of the delayed (controlling) approach is between 1550 and 1650 vehicles per hour.

Based on the above, it is recommended that for single lane roundabouts the relevant point on Figure 6.4 be found. If this point falls outside of the green area then it is suggested that alternative means to increase roundabout capacity be explored, rather than installing roundabout metering signals.



Source: (Natalizio 2005)

Figure 6.4 : Single Lane Roundabouts - Flow Conditions on the Controlling Approach that would benefit by installing Metering Signals

A case study example of the partial signalisation of an existing roundabout by installing metering signals is given in Appendix D.

6.2 Full Signalisation of Roundabouts

In the full signalisation of a roundabout, the signals control both entering traffic and circulating traffic at each entry but are not used to control traffic that is exiting from the circulating roadway. One of the major advantages of signalising a roundabout from a capacity point of view is that, in its simplest form, each signalised junction can be operated on a two-phase system, as illustrated in Figure 6.5. However, for full signalisation to be successful, the roundabout must be sufficiently large to accommodate any necessary queuing in the circulating roadway, or be of such a size that it can be operated without excessive lost time. Furthermore the cycle length should be comparatively short (50 to 60 seconds is preferred) to limit the internal queue lengths arising from the right turning traffic.

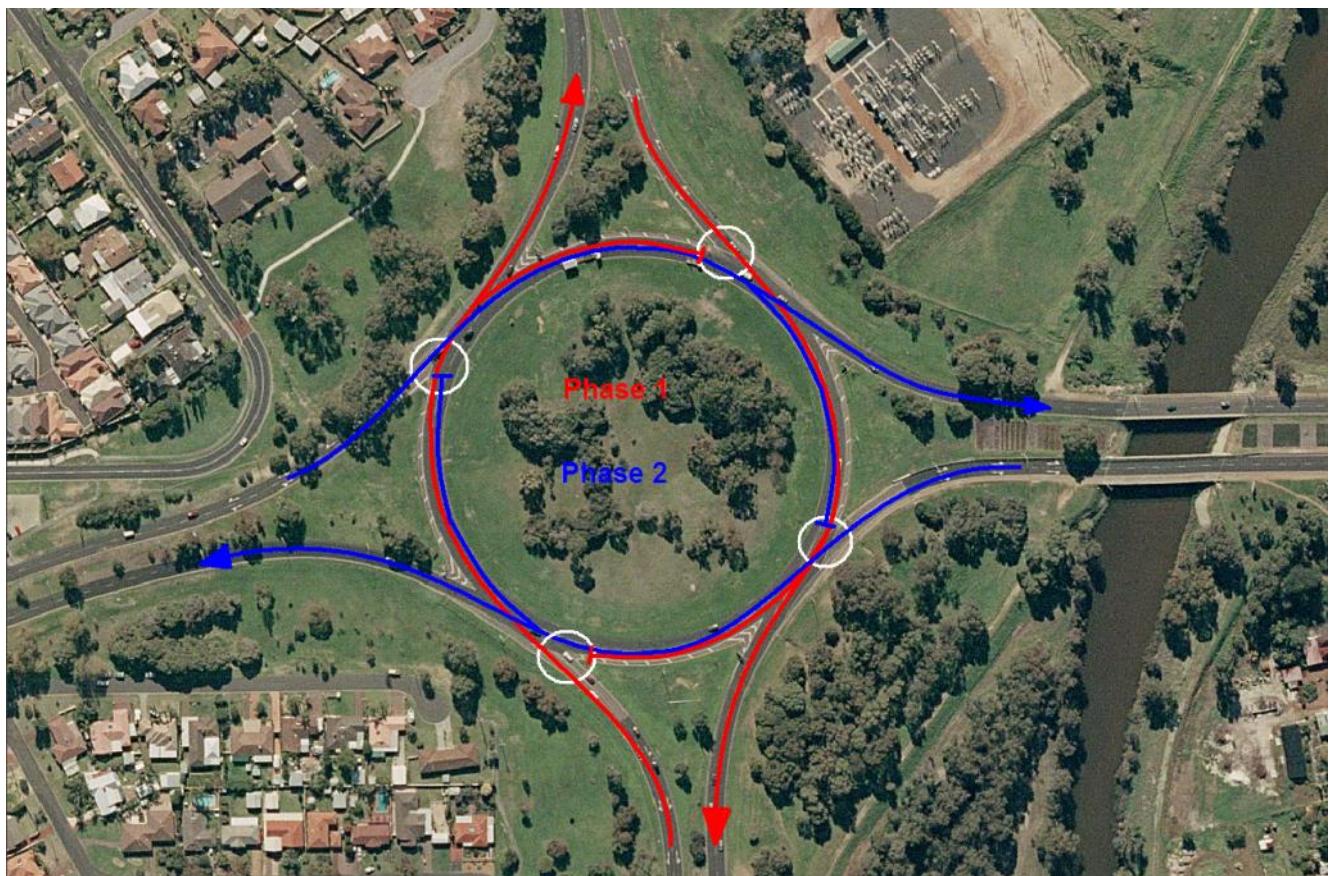


Figure 6.5: Two-phase Operation of Fully Signalised Roundabout

A decision to fully signalise a roundabout should be based on traffic analyses to establish the performance of the signalised roundabout compared to other options, e.g. replacement with a conventional signalised layout. An initial appraisal of the suitability of the roundabout for full signalisation may be based on the following capacity check methodology (Dept. for Transport, April 2009):

Individual signalised nodes on a roundabout will usually operate as simple two-stage signals. Once a draft lane flow diagram has been drawn up, a simple check will show if a node will have sufficient capacity. If the highest individual lane flow from each of the two stop lines (i.e. critical lanes) are added together, then a total less than about 1500 pcu/h would indicate that there is likely to be sufficient capacity. This is based on an assumed cycle time of 60 seconds, 5 second intergreens, a lane saturation flow of 1900 pcu/h and a degree of saturation of 90 percent.

If the above methodology indicates that full signalisation of the roundabout may be promising, a further detailed analysis may be carried out using SIDRA INTERSECTION 6, making use of the network analysis methodologies or LINSIG.

Currently in WA there is one fully signalised roundabout: Eelup Rotary in Bunbury. The background and success of this signalised roundabout has been detailed in Appendix C.

6.3 Future of Signal Control at Roundabouts in Western Australia

Signalisation of roundabouts is used extensively in the United Kingdom to improve capacity, reduce delays, reduce crashes and address pedestrian and cyclist difficulties. Contrary to current practice in Australia, roundabouts may be operated under:

- Full or Partial Signalisation
- Full or Part-time Signalling
- Indirect or Direct Signal Control

More detail on signalised roundabouts in the UK is provided in Commentary 3.

In WA, both indirect and direct signal control retains the safety benefits of roundabouts as traffic speeds are relatively slow: the safety of roundabout operation at all times of operation will be safer than conventional signalised intersections.

Roundabout metering signals (indirect control) - Based on the success of the implementation of roundabout metering signals at Point Lewis Rotary (and the proven effectiveness at a number of sites elsewhere in Australia), the use of metering signals would appear to have significant potential. Recent additions to the SIDRA INTERSECTION analysis program have enhanced its ability to analyse roundabouts with one or more legs metered. This form of control is generally operated under part-time control - where the signals are switched on or off at set times (generally peak periods) or under certain traffic conditions by queue detectors.

Direct Signal Control – There is no doubt that the full signalisation of the Eelup Rotary has been an outstanding success, both from a safety and operational perspective. However, because of the internal storage requirements, it may only be feasible to provide direct signal control at large roundabouts, which limits its applicability.

It is considered that direct signal control warrants further investigation and assessment to determine its potential to improve the operation of roundabouts in WA. This form of control may be a solution to addressing delays at congested sites where indirect signal control may not be appropriate. If direct signal control is able to provide the benefits achieved in the UK, this may avoid significant costs to replace roundabouts with signals.

However, further investigation would be needed to determine the suitability of implementing part-time direct signal control, especially in the light of the UK experience that it could lead to potential safety problems, no provision for pedestrians and cyclists and a compromised layout. Nevertheless, it may be advantageous to retain the operational benefits of roundabouts at off peak periods provided the roundabout can cater for the types of multi-combinational vehicles expected to use the roundabout.

7. PROCESS FOR CHOOSING INTERSECTION CONTROL TYPE

The consideration and balancing of the site specific items shown in Table 4.3, as well as appropriate analyses and evaluation, are essential parts of determining an appropriate form of control for an intersection.

The philosophy adopted in these guidelines for choosing between traffic signal control and roundabout control has been to balance all the relevant factors to arrive at the most cost effective solution that meets all (or the most) relevant criteria. However, given that from a Safe System point of view a roundabout design minimises the number and severity of vehicular conflicts and hence is considered the safer of the two options, it is suggested that the design process start with the assumption that a roundabout is the preferred traffic control type (unless the design can be shown to offer similar safety characteristics as a roundabout) and only if it cannot meet all necessary design requirements should traffic signal control be considered.

The type of intersection control can have a significant impact on the amount of land required as well as access to and from adjacent properties. For these reasons it is important that the intersection control type be determined early on in the planning or design process in order to define or redefine appropriate cadastral boundaries. Under certain constrained conditions, an initial analysis of options may be sufficient to eliminate any intersection control types as “fatal flaws”, although as a minimum it will generally be necessary to take the option(s) to a concept design stage. In some cases it will be necessary to take the concept design to a preliminary design standard.

Figure 7.1 shows a flow chart (Flow Chart 1) that should be used to determine the appropriate control type for intersections on major roads. The outcome from this process will either be that roundabout control is suitable or that the designer should follow Flow Chart 2 (Figure 7.2) to determine a suitable signalised layout. During the process relevant checks are made to ensure that all factors identified in Section 4 are considered and are satisfactorily addressed.

Once this process is completed, the designer should document the results summarising the appropriate information for the project approval decision. This is provided in tabular format in Appendix E in the form of a pro-forma.

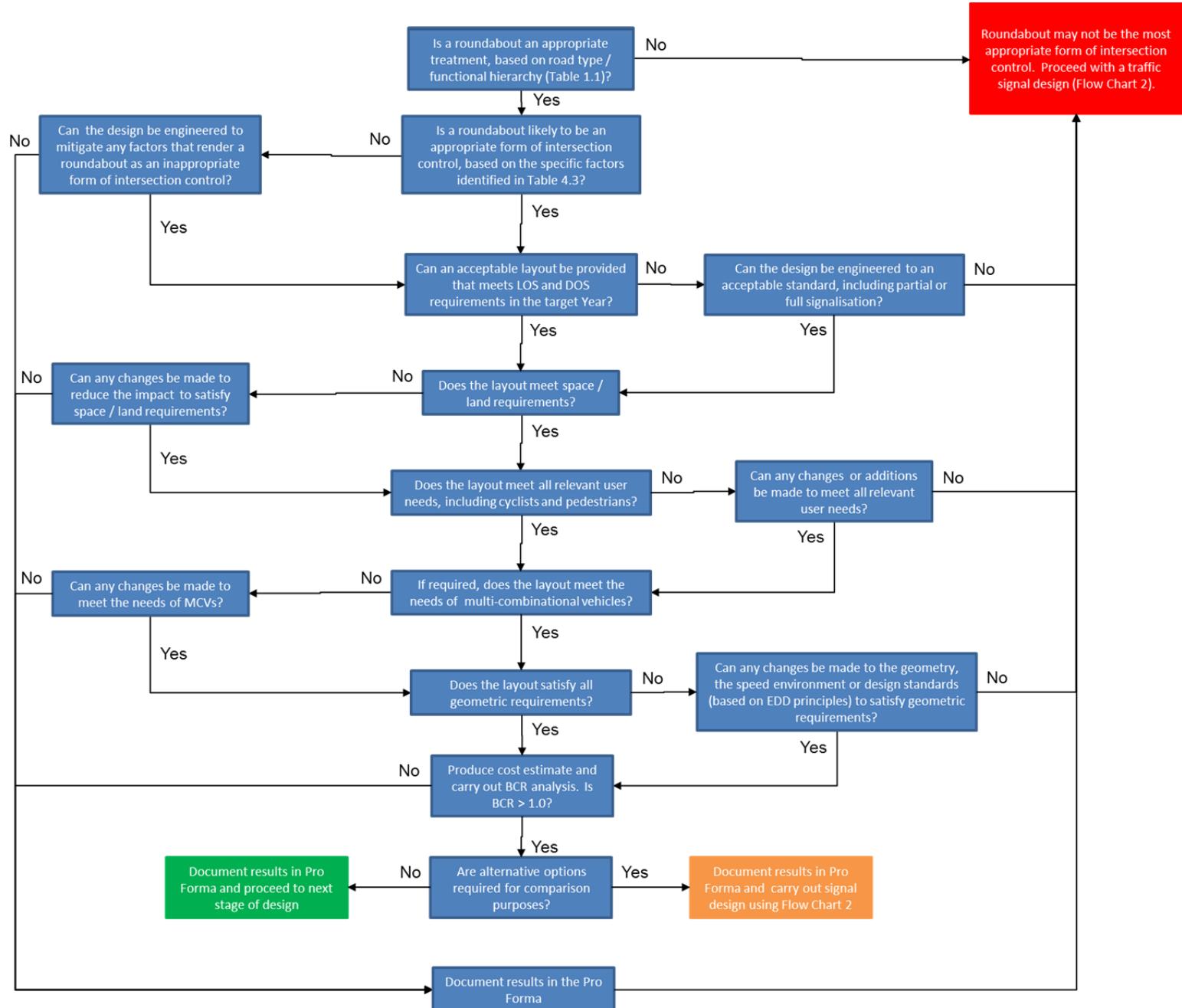


Figure 7.1: Flow Chart 1 – Process for Choosing between Roundabout and Traffic Signal Control

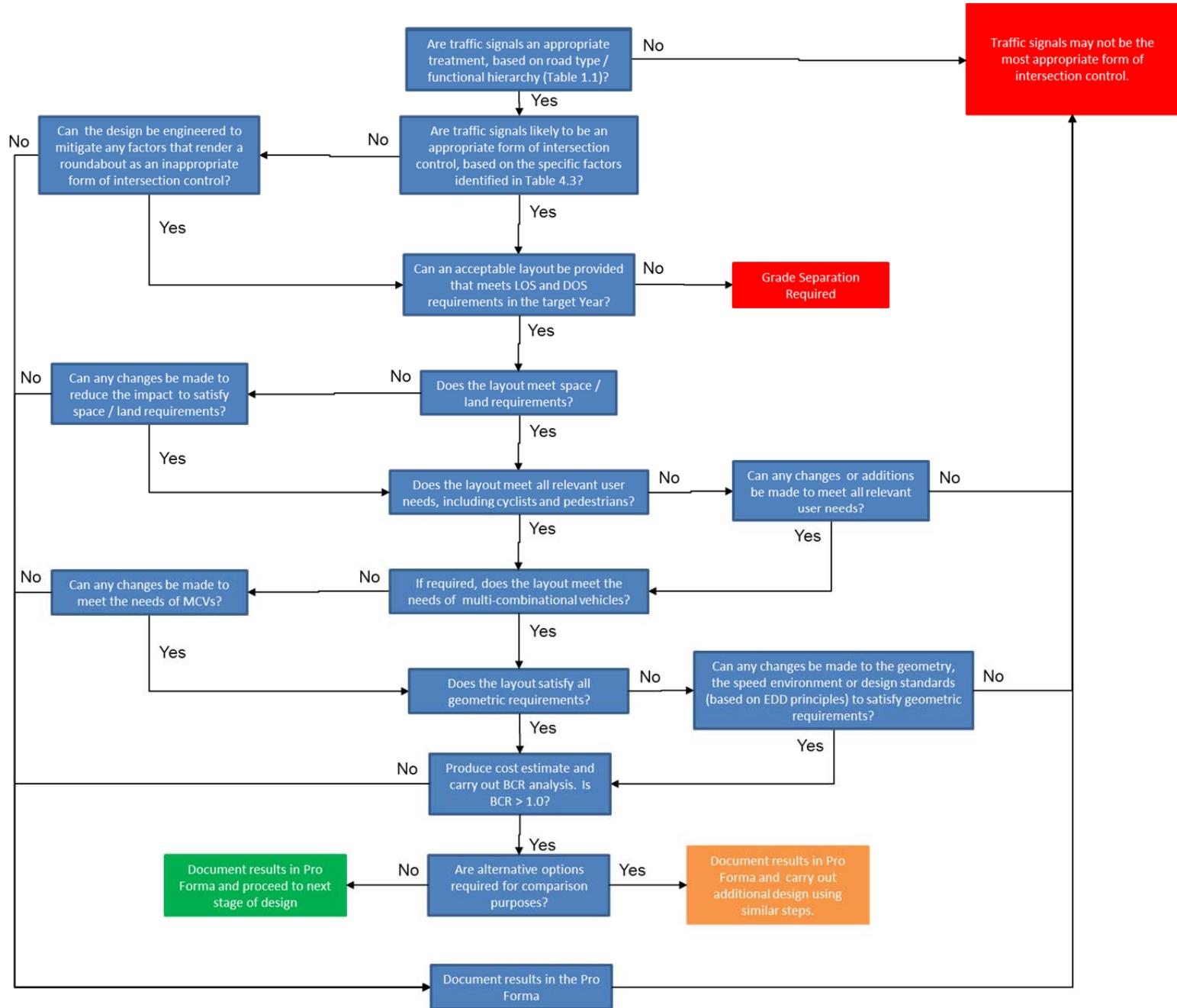


Figure 7.2: Flow Chart 2 –Traffic Signal Control Design Process

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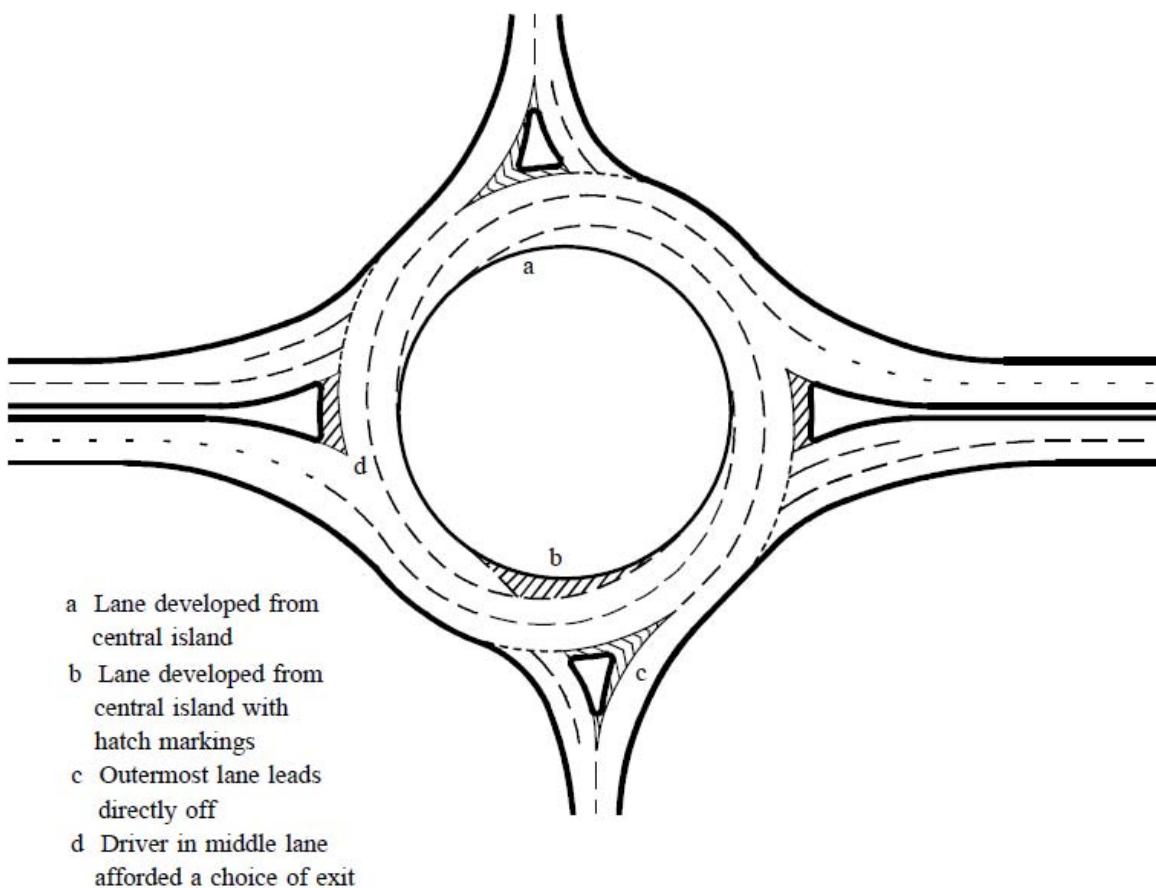
9. COMMENTARIES

Commentary 1

A spiral marking system involves one or more of a series of lane gains and lane drops around the circulatory carriageway so that drivers enter in the lane appropriate for their desired exit, and follow the lane around the roundabout to be led off at that exit (Fig C1.1). The width of a particular exit will determine how many circulating lanes lead off the roundabout.

The spiral markings may be developed from the central island by means of line markings, or by hatch markings until a full lane width is available. Line markings are appropriate on normal roundabouts, but where the inscribed circle and central island are small and/or the number of arms is high, the first two or three markings leading to the full lane width may be omitted. Hatch markings are appropriate on larger diameter normal roundabouts or grade separated roundabouts where the number of circulating lanes is to be varied to aid general operation.

Spiral markings are appropriate on large roundabouts where they can be used to guide drivers around the roundabout to their desired exit, whilst maximising the use of the circulating space and reducing potential conflict between adjacent vehicles. The markings can also cater for heavily biased turning proportions, since the circulatory width may be divided according to traffic demand.



Source: Design Manual for Roads and Bridges TA78/97, Design of Road Markings at Roundabouts, Highways Agency, November 1997

Figure C1.1 : Spiral Markings

Single lane exits adjacent to two circulating lanes

For multi-lane roundabouts, the standard exit line marking treatment alone does not appropriately allow for single lane exits adjacent to two circulating lanes in all cases. This typically occurs in the following instances:

- two-lane capacity is required from an entry leg to exits beyond the second exit leg;
- two-lane capacity is required for a right-turn; and
- two lane capacity is required for a through movement from an entry leg and a left-turn leg is present at a substantial distance from the entry leg

As a consequence of providing two-lane capacity from Leg 1 to Leg 4 of Example A in Figure C1.2, there is a requirement to drop a lane at the exit preceding Leg 4 (i.e. Leg 3 must be a single lane exit as shown). This helps mitigate exiting/circulating accidents at Leg 3 for traffic coming solely from Leg 1. However a problem still exists, as motorists entering from Leg 4 or Leg 5 and exiting at Leg 3 are required to cross the exit line marking as illustrated by Example B in Figure C1.2. A similar problem will occur for Examples C and D in Figure C1.2.

As a consequence of providing two lane capacity from Leg 1 to Leg 4 (of Example A in Figure C1.2), there is a requirement to provide motorists entering from Leg 4 or Leg 5 and destined for Leg 3 with an opportunity to get to the outer lane (and avoid a lane change at the exit). This can be achieved by using “spiral” continuity line marking as shown in Examples A and B of Figure C1.3. Examples C and D of Figure C1.3 illustrate this same concept for a four legged and a three legged, multi-lane roundabout respectively.

For Examples C and D of Figure C1.3, there are also spirals adjacent Legs 4 and 3 respectively. For these examples, the “spiral” line marking also provides the driver already circulating on the roundabout with an opportunity to exit in either the left or right hand lane of Leg 1. This is especially important were there are downstream accesses on Leg 1. The ability to exit in either lane will minimise lane changes for drivers turning into downstream accesses.

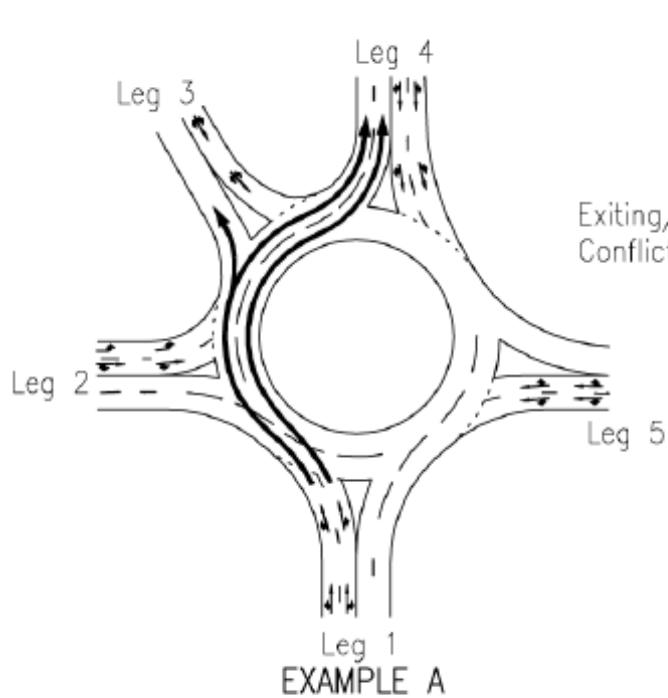
“Spiral” line-marking, however does not completely resolve driver confusion with regard to negotiating these roundabouts. For some paths through the roundabout, drivers will need to cross the continuity line, for other paths they will need to follow it. Examples of this are described below:

- Examples A and B of Figure C1.3
 - When travelling from Leg 1 to Leg 4 in the inner lane, a motorist is to cross the continuity line;
 - When travelling from Leg 5 to Leg 3 or from Leg 4 to Leg 3, a motorist must follow the continuity line;
 - When travelling from Leg 5 to Leg 5 (i.e. a U-turn from Leg 5), a motorist is to cross the continuity line; and
 - When travelling from Leg 5 to Leg 4 or from Leg 4 to Leg 4 (i.e. a U-turn from Leg 4), a motorist can either cross or follow the continuity line.
- Example C of Figure C1.3
 - When travelling from Leg 1 to Leg 4 on the inner lane, a motorist is to cross the continuity line;
 - When travelling from Leg 4 to Leg 3, a motorist is to follow the continuity line;
 - When travelling from Leg 3 to Leg 3 (i.e. a U-turn from Leg 3), a motorist is to cross the first continuity line, then follow the second continuity line; and

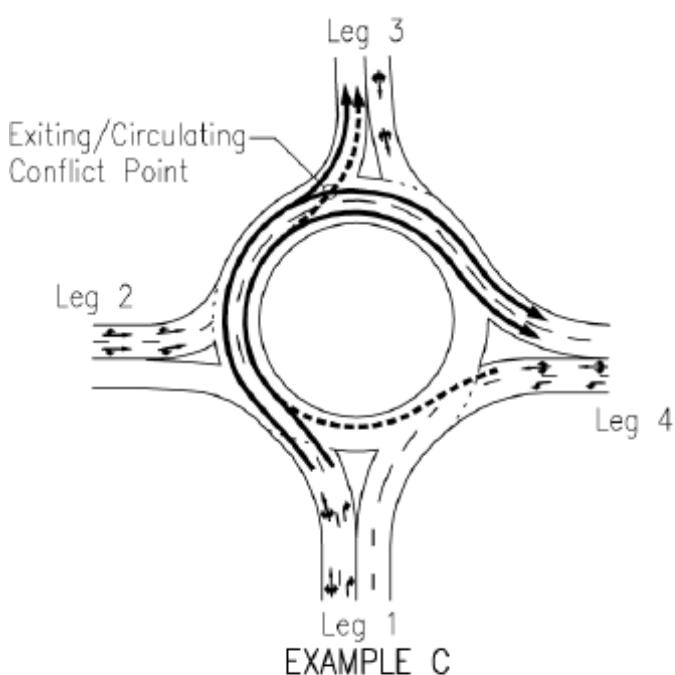
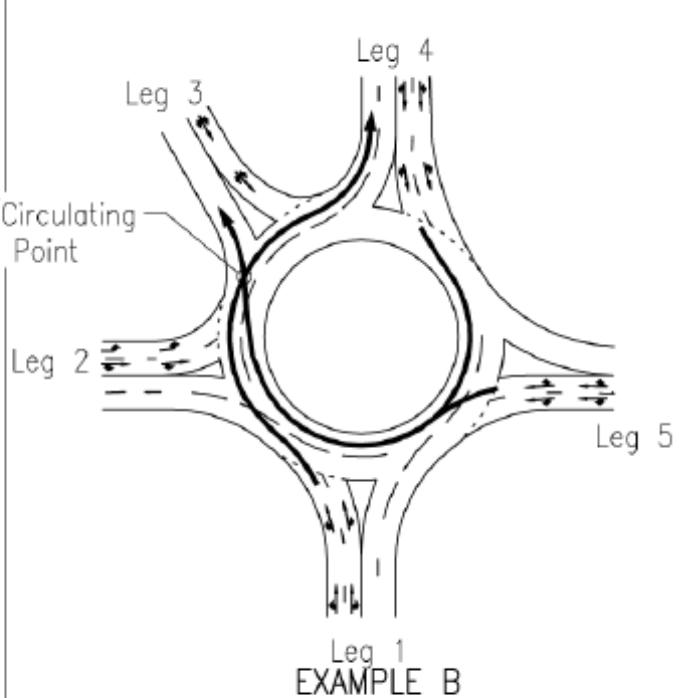
- When travelling from Leg 4 to Leg 4 (i.e. a U-turn form Leg 4), a motorist can either follow or cross the continuity line.
- Example D of Figure C1.3
 - When travelling from Leg 1 to Leg 3 on the inner lane, a motorist is to cross the continuity line;
 - When travelling from Leg 2 to Leg 2 (i.e. a U-turn from Leg 2), a motorist is to cross the first continuity line, then follow the second continuity line;
 - When travelling from Leg 3 to Leg 2, a motorist is to follow the continuity, and
 - When travelling from Leg 3 to Leg 3 (i.e. a U-turn from Leg 3), a motorist can either follow or cross the continuity line.

It is very difficult to advise drivers of the above requirements for all movements through these roundabouts, particularly with regard to when/how a driver is required to follow the spiral line markings (i.e. change from the inner circulating lane to the outer circulating lane for the movements above). Advance intersection direction signs do not show the required action in this case. For this reason, drivers faced with the “spiral” line marking may be confused as to whether to cross the “spiral” line marking or not.

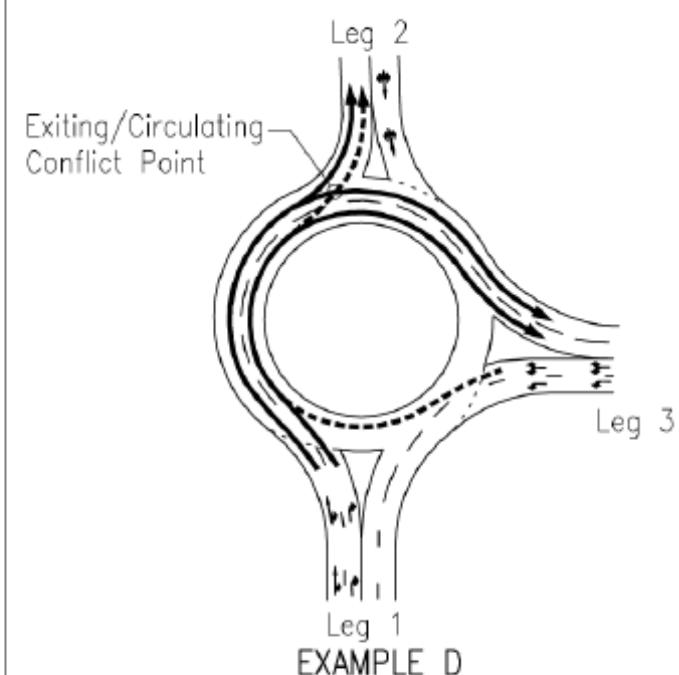
For the above reasons, two-lane capacity from an entry leg to an exit beyond the second exit leg is undesirable and should only be considered for existing roundabouts where there is a capacity problem. “Spiral” line making should only be considered as a solution to minimising operational problems on existing roundabouts where no other solution is feasible. Careful consideration needs to be given to the use/provision of “spiral” markings and, in all cases, advice should be sought from the Traffic Engineering Standards Manager or Traffic Manager Design in the Road & Traffic Engineering Branch prior to their installation.



2 Lane capacity from Leg 1 to Leg 4 is achieved by providing a single lane exit at Leg 3.



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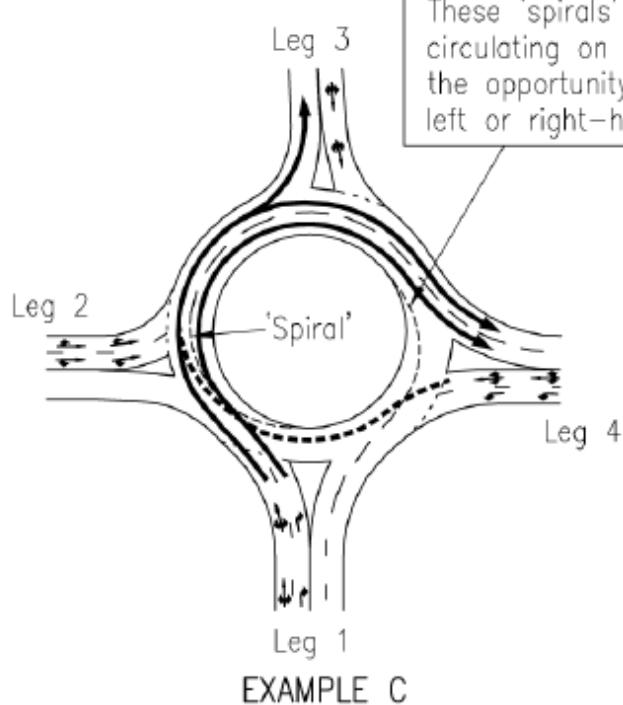
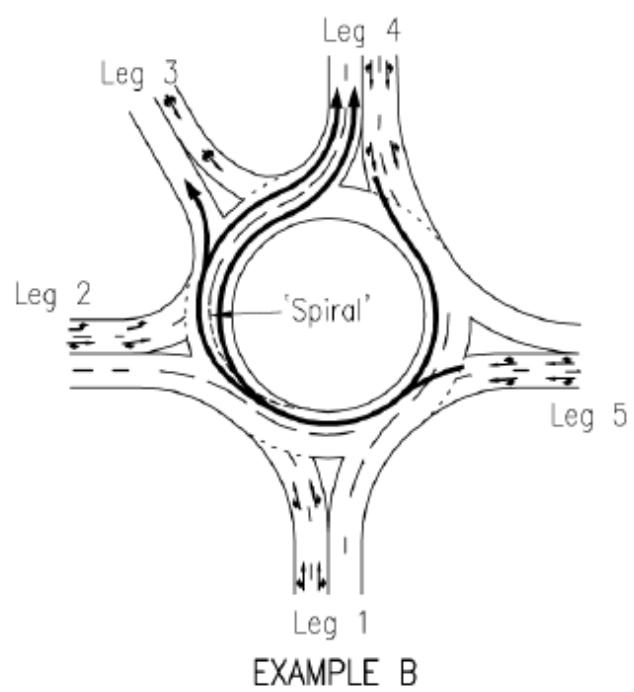
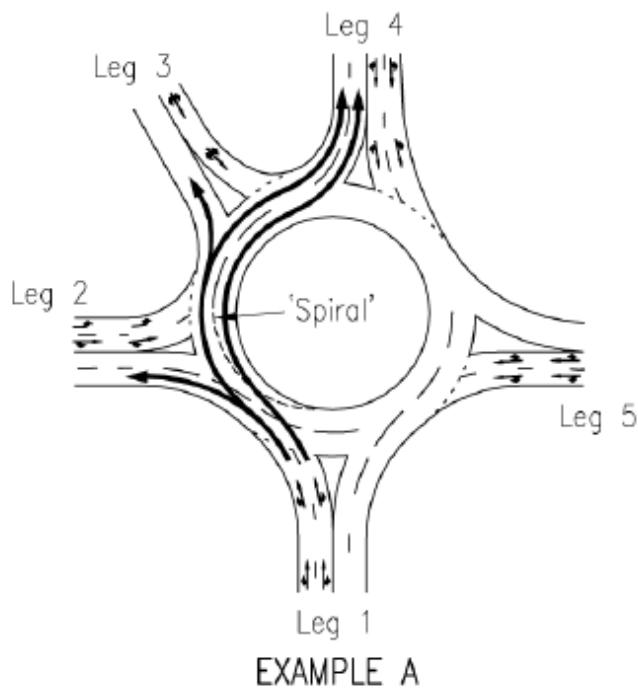


2 Lane capacity from Leg 1 to Leg 3 is achieved by providing a single lane exit at Leg 2.

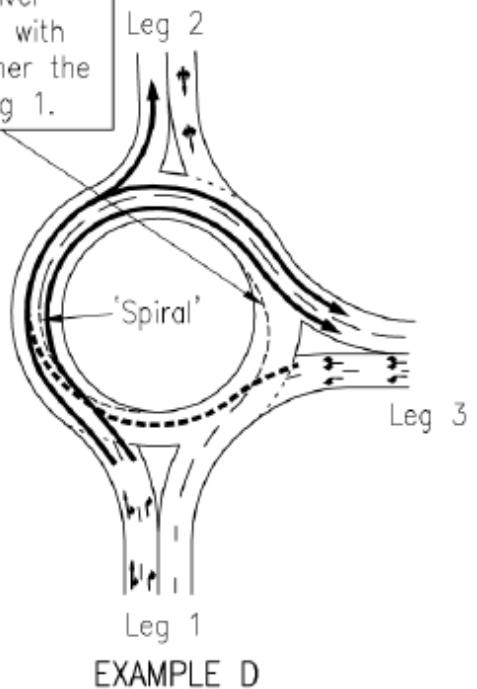
The geometry in these examples should not be used for the design of new roundabouts. If the examples shown in this figure were existing roundabouts, they would require 'spiral' line marking. Without the use of 'spiral' line marking, exiting/circulating conflicts are compounded at single lane exits adjacent to two circulating lanes.

Source: Road Planning and Design Manual , Queensland Department of Main Roads, January 2006

Figure C1.2 Examples showing potential conflicts arising without the "spiral" line marking system



These 'spirals' provide the driver circulating on the roundabout with the opportunity to exit in either the left or right-hand lane of Leg 1.



The geometry in these examples should not be used for the design of new roundabouts. These examples show the use of 'spiral' linemarking which is required to help guide motorists onto single lane exits adjacent to two circulating lanes. 'Spirals' are generally only suitable for retrofitting to existing roundabouts.

Source: Road Planning and Design Manual , Queensland Department of Main Roads, January 2006

Figure C1.3 Examples showing the use of the "spiral" line marking system for the examples shown in Figure C1.2



Figure C1.4 Example of “Spiral” Markings on a Signalised Roundabout in Bunbury

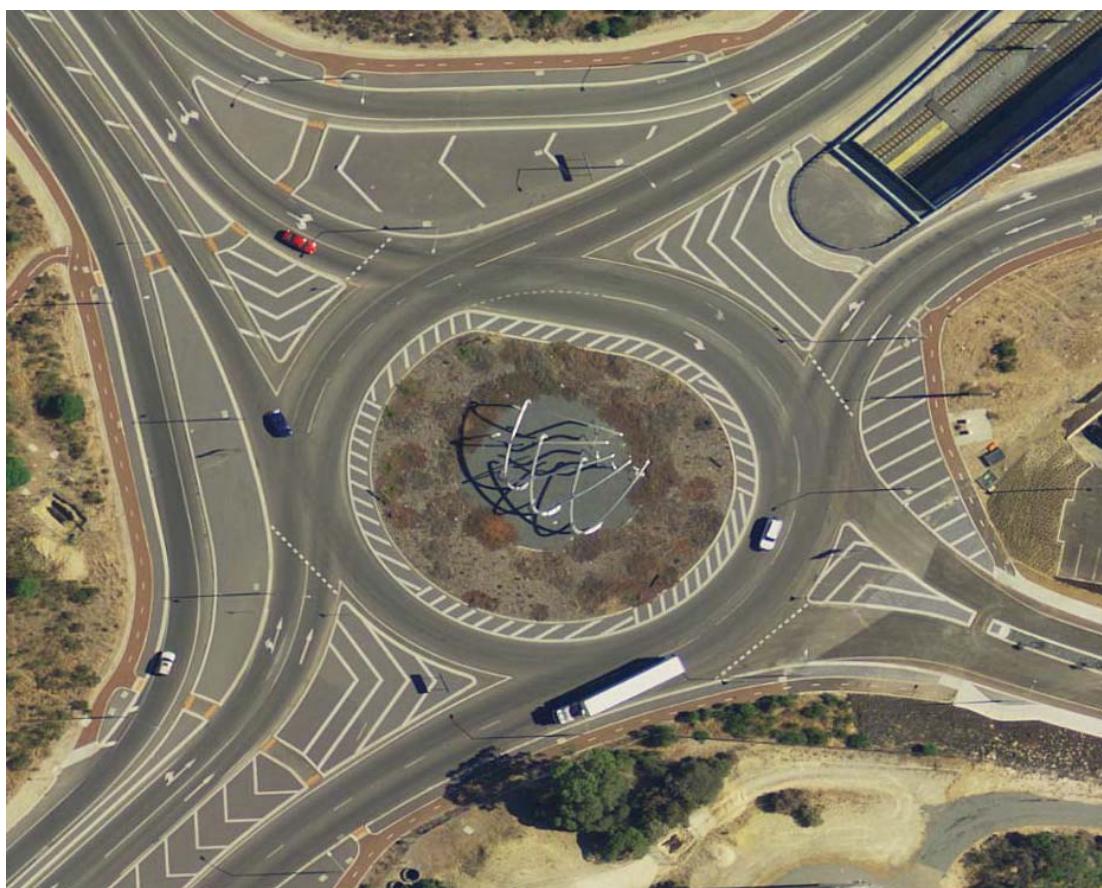
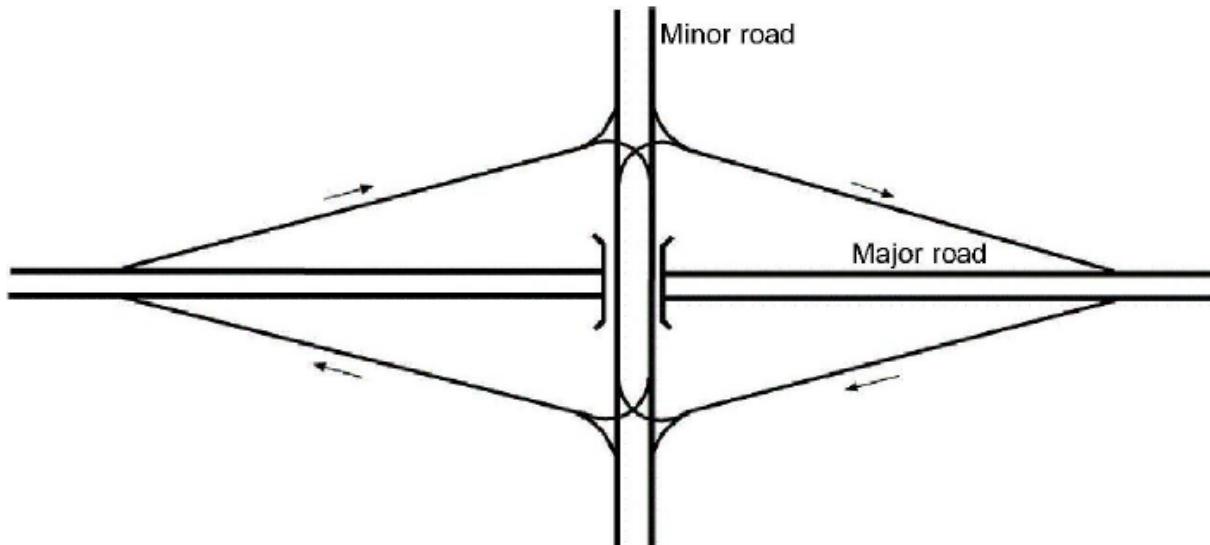


Figure C1.5 Example of “Spiral” Markings on a Roundabout in Mandurah to Facilitate Double Right Turns

COMMENTARY 2

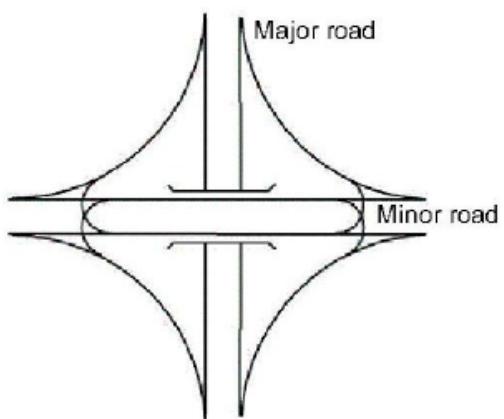
Figure C2.1 illustrates the conventional diamond interchange that is the most common form of service interchange. The advantages and disadvantages of the conventional diamond also apply to the variations of the diamond interchange shown in Figures C2.2 to C2.6. The advantages and disadvantages associated with Figures C2.2 to C2.6 are peculiar to that form of diamond interchange.



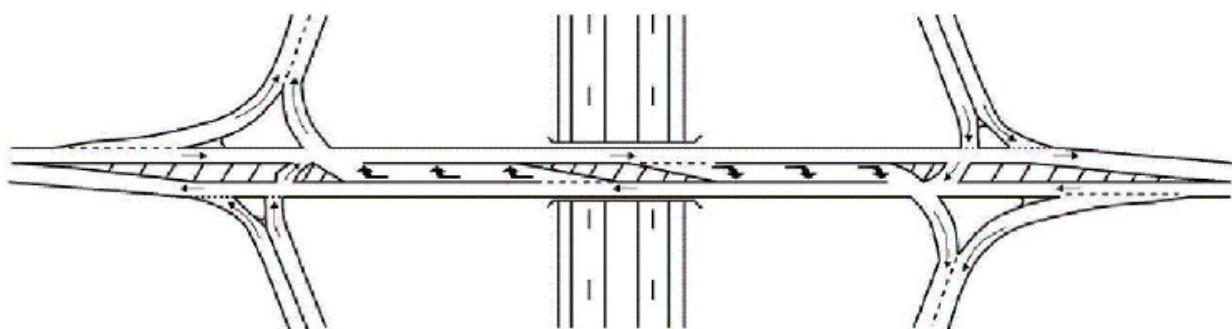
| General Comment | Advantages | Disadvantages |
|--|---|--|
| <ul style="list-style-type: none"> The conventional diamond is the most common form of service interchange and its layout is well-understood by drivers. Variations are spread diamond (Figure C2.2), with ramps a significant distance apart, and closed diamond (Figure C2.3), with ramp terminals relatively close to the major road alignment. | <ul style="list-style-type: none"> Provides high-standard single exits and entrances in advance of and beyond the structure respectively. Where the major road passes under the minor road, the grades of the ramps assist the deceleration of existing traffic and the acceleration of entering traffic. Single exit features simplifies major road signing. There is no need for speed change lanes on or under the structure resulting in reduced cost. Does not result in weaving on major road. Ramps can allow for over-height loads that are unable to pass beneath an overpass of the major road. Design is economical in property use and construction costs. | <ul style="list-style-type: none"> Results in conflicting movements on the minor road, which limit capacity and safety. Right-turns from the minor road may overlap leading to inefficiencies in traffic signal phasing. Where the minor road crosses over the major road, provision of adequate visibility at the ramp / minor road intersections may be difficult. There is a possibility of wrong-way movements. Right-turning traffic from the major road is obliged to stop or give way at the minor road. Additional lanes may be required for storage. If there is no left-turn acceleration lane, left-turning traffic is also obliged to give way. There is little possibility of allowing for future expansion of the interchange. |

SOURCE: (Austroads, 2013)

Figure C2.1: Conventional Diamond Interchange



(a) Spread diamond

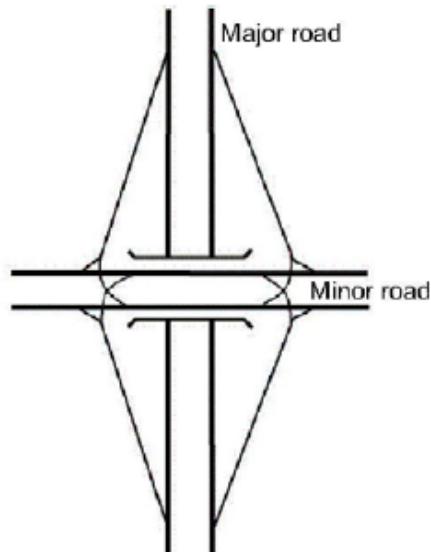


Detail for (a)

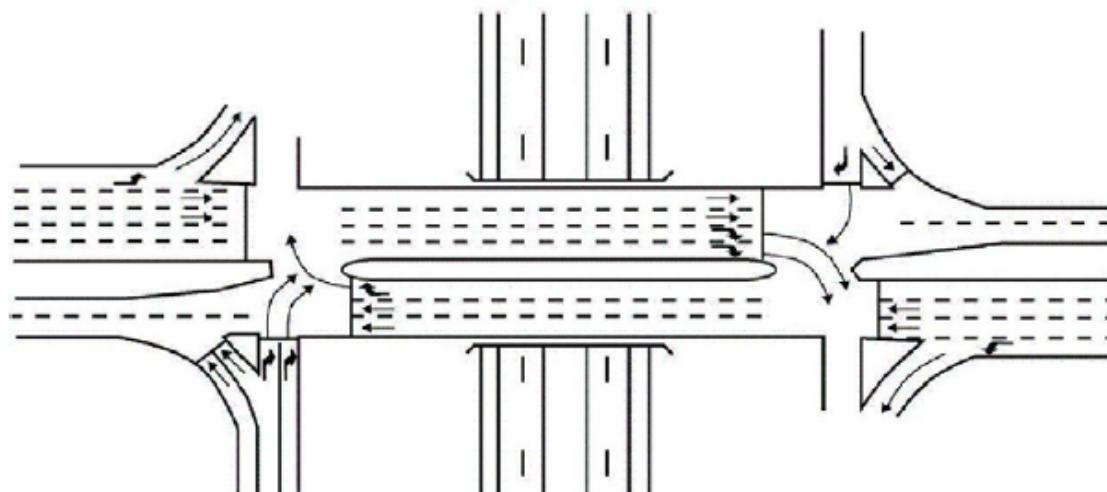
| General Comment | Advantages | Disadvantages |
|--|---|--|
| <ul style="list-style-type: none"> The spread diamond is the most common type in rural Australia. Typically, ramp terminals are approximately 500m apart along the minor road, terminals being 250m either side of the major road centreline to meet safe intersection sight distance (SISD) requirements. | <ul style="list-style-type: none"> Where the intersecting road passes over the major road, only one bridge is usually required. Compared with the closed diamond (Figure C2.3): <ul style="list-style-type: none"> Has smaller embankments and lower earthwork's costs. The right-turn lanes are on an embankment rather than on the bridge, reducing costs. Unlikely to require additional measures to address sight distance issues, compared to closed diamond interchanges. | <ul style="list-style-type: none"> Requires more land than conventional or closed diamond layouts so not as applicable in urban areas as in rural areas.. |

SOURCE: (Austroads, 2013)

Figure C2.2: Spread Diamond Interchange



(b) Closed diamond

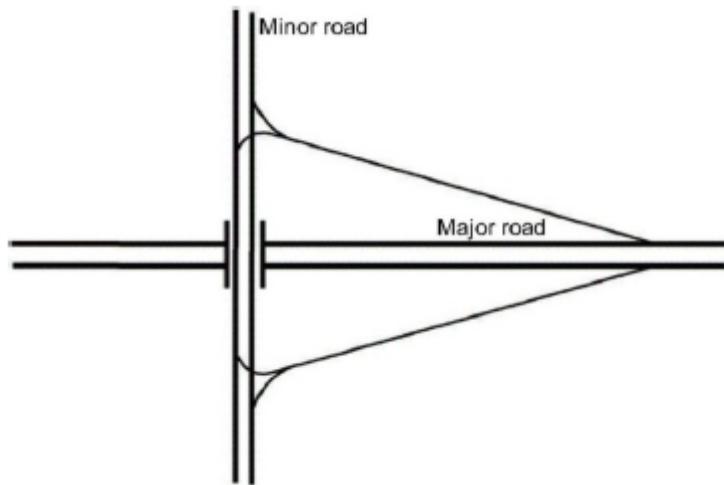


Detail for (b)

| General Comment | Advantages | Disadvantages |
|---|---|--|
| <ul style="list-style-type: none"> The closed diamond has ramp terminals relatively close to the major road alignment. Common in urban areas because of high land costs and use of sophisticated traffic signal coordination systems. | <ul style="list-style-type: none"> Has a smaller land requirement than conventional or spread diamond layouts. | <ul style="list-style-type: none"> Effectiveness may be limited by the capacity of the at-grade terminals. For a minor road over a major road, a closed diamond may need a very wide structure to accommodate back-to-back right-turn lanes (perhaps double turns) and to meet sight distance requirements at ramp terminals. Measures may be required to ensure that bridge barriers do not impede sight distance on the minor road. Limited storage between intersections may compromise signal phasing and intersection capacity. |

SOURCE: (Austroads, 2013)

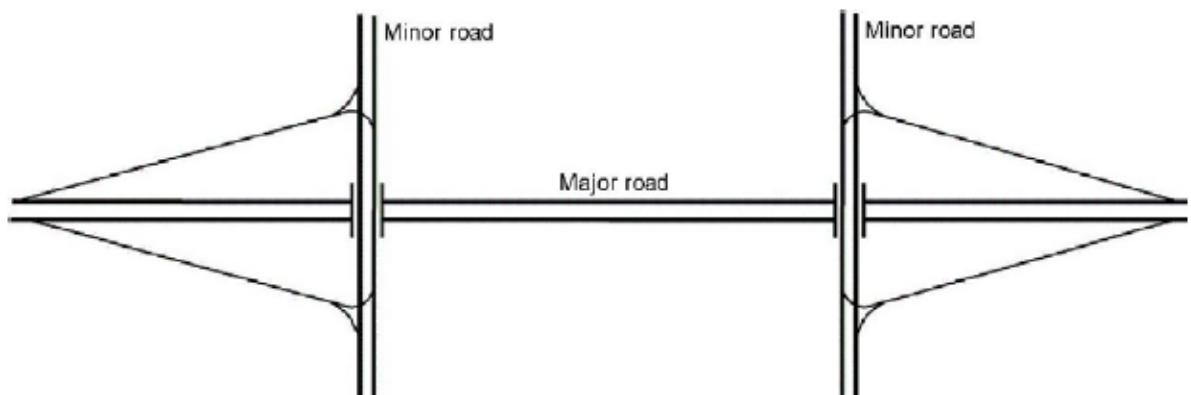
Figure C2.3: Closed Diamond Interchange



| General Comment | Advantages | Disadvantages |
|--|---|--|
| <ul style="list-style-type: none"> The half diamond provides entry to and exit from the major road on only one side of the intersecting road. | <ul style="list-style-type: none"> Often used in urban areas where they can be appropriate because of the close spacing of intersecting roads along a freeway. May also be appropriate because of network requirements and topography. Simpler intersections because of limited number of movements. | <ul style="list-style-type: none"> Not favoured in rural areas because interchanges usually are more widely spaced, and drivers unfamiliar with the area may be disconcerted to find that they cannot re-join the major road at the same interchange at which they left it. In the case of closed half diamond interchanges, measures may be required to ensure that bridge barriers do not impede sight distance on the minor road. |

SOURCE: (Austroads, 2013)

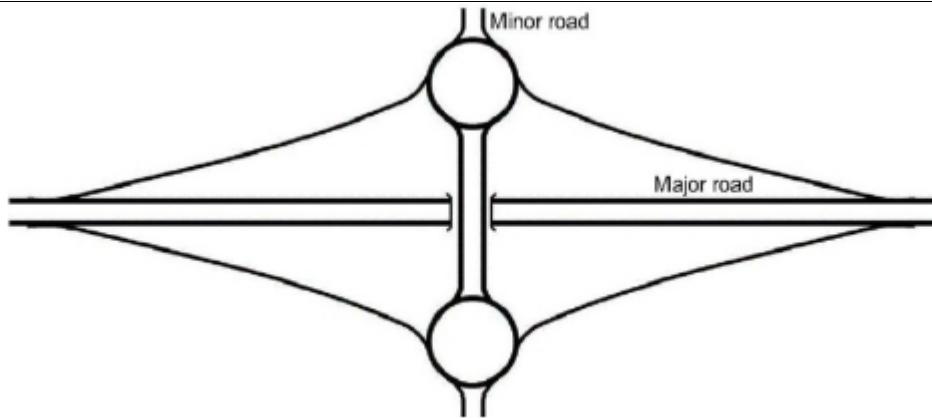
Figure C2.4: Half Diamond Interchange



| General Comment | Advantages | Disadvantages |
|---|--|---|
| <ul style="list-style-type: none"> The split diamond is essentially two half diamonds a short distance apart, each providing entry to (and exit from) the major road in the opposite direction from the other. | <ul style="list-style-type: none"> Provides the same advantages as the half diamond but permits access to and from the major road in both directions. Provides the opportunity to connect the two interchanges via one-way frontage roads. | <ul style="list-style-type: none"> Can create navigational problems similar to those for half diamond, as return routes and signage are more complicated, particularly where frontage roads cannot be provided to directly connect the two half diamonds making up the split interchange. In the case of closed split diamond interchanges, measures may be required to ensure that bridge barriers do not impede sight distance on the minor road. |

SOURCE: (Austroads, 2013)

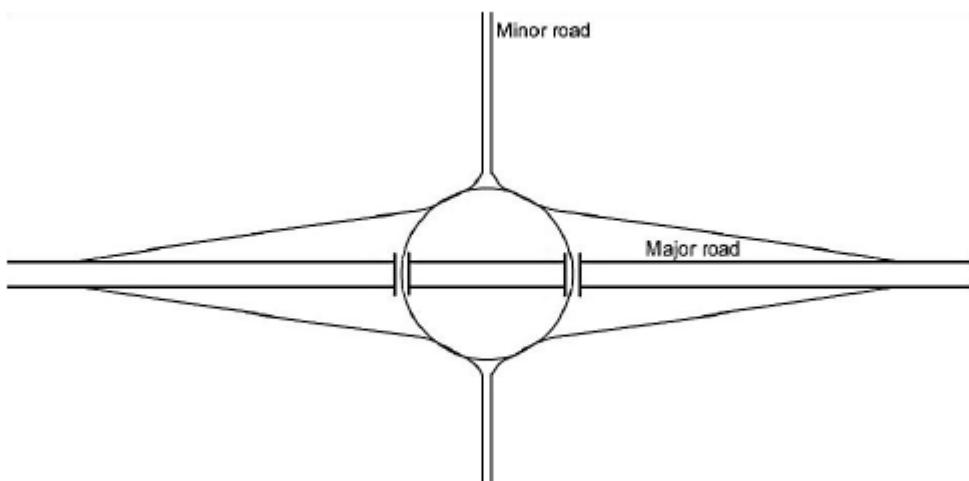
Figure C2.5: Split Diamond Interchange



| General Comment | Advantages | Disadvantages |
|--|---|---|
| <ul style="list-style-type: none"> The intersections of the diamond ramps with the minor road are designed as roundabouts | <ul style="list-style-type: none"> With certain mixes of traffic volumes on its various elements, this form of interchange can provide fewer delays and a higher level of safety than alternatives. Requires a relatively narrow structure since turn pockets are not usually required. | <ul style="list-style-type: none"> Requires the availability of sufficient space for its implementation. |

SOURCE: (Austroads, 2013)

Figure C2.6: Diamond Interchange with Roundabout Terminals (“Spectacles” Type)



| General Comment | Advantages | Disadvantages |
|--|---|---|
| <ul style="list-style-type: none"> The grade separated roundabout is an alternative to the diamond interchange and is suitable for both urban and rural situations involving moderate requirements for capacity. The numbers of lanes at entries and exits are comparable to those in a diamond interchange with roundabout terminals. Oval shaped roundabout enables entries and exits to be positioned at 90° to one another. | <ul style="list-style-type: none"> Provides high standard single exits and entrances in advance of and beyond the structure respectively. Where the major road passes under the minor road, the grades of the ramps assist the deceleration of existing traffic and the acceleration of entering traffic. Single exit feature simplifies major road signing. Reduces possibility of wrong-way movements. Has lower average delay than for signalised diamond for low to moderately high traffic volumes. | <ul style="list-style-type: none"> Is higher cost than conventional diamond – two overpasses or underpasses are required. Large land requirements. Parapets could interrupt the sight lines of drivers. May need to widen the bridges to meet sight distance requirements at the exit ramp terminals. Capacity of the interchange as a whole is limited by the capacity of the roundabout. |

SOURCE: (Austroads, 2013)

Figure C2.7: Grade Separated Roundabout

COMMENTARY 3

Signalisation of roundabouts is used extensively in the United Kingdom to improve capacity, reduce delays, reduce crashes and address pedestrian and cyclist difficulties. Local Transport Note 1/09 (Dept. for Transport, April 2009) was developed to assist those involved in the design and operation of signalised roundabouts by identifying the issues that need to be addressed and providing guidance on how they can be dealt with. Local Transport Note 1/09 should be read in conjunction with the *Design Manual for Roads and Bridges* (Highways Agency, 2004). These documents provide a valuable resource for designers and engineers in WA, although it should be remembered that standards and regulations do differ. Moreover, the fleet types in the UK differ substantially from Western Australian fleet types: in the UK trucks are less than 50 tonnes gross, whereas we have 128 tonnes gross trucks, lengths are different and driver training and behaviour is different.

Local Transport Note 1/09 states that “*No two roundabouts are the same – there are no ‘standard’ solutions.*” The range and type of signalised roundabout is complicated by considering the number of parameters affecting control strategies. Roundabouts may be operated under:

- Full or Partial Signalisation
- Full or Part-time Signalling
- Indirect or Direct Signal Control

Full or Partial Signalisation

Partial control of a roundabout (signalisation of one or more, but not all, approaches) is often employed where delays do not occur on all legs. Sometimes, the installation of a single signal at an entry is all that is needed to solve a particular problem.

Consideration could be given to leaving one leg under priority control if safe operation and sufficient capacity can be achieved and there is sufficient storage length downstream at the next stop line within the circulating roadway. Partial signalisation is particularly useful at smaller roundabouts since it requires less storage space for queuing within the roundabout.

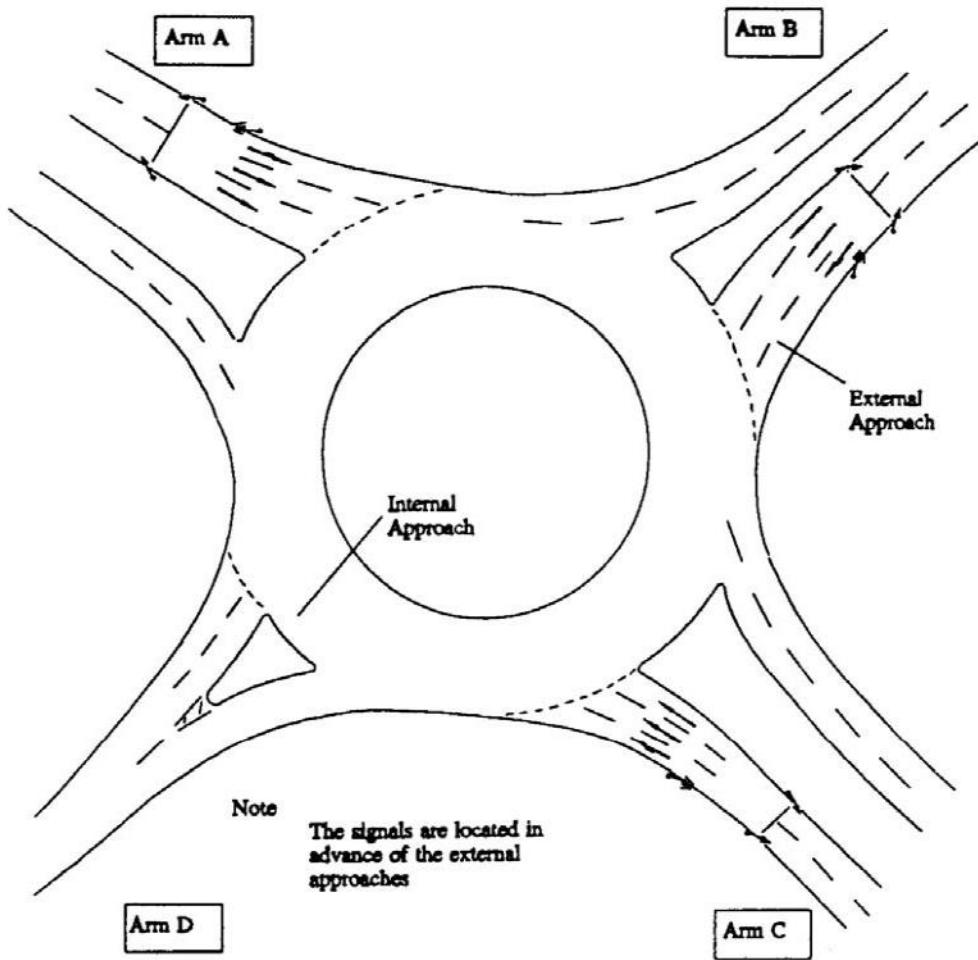
Full or Part-time Signalling

In the past, where capacity problems at roundabouts occur primarily during peak periods, it has been common practice to implement signal control on a part-time basis. However, part-time signals can result in potential safety problems, no provision for pedestrians and cyclists and a compromised layout. There has generally been a move away from using part-time signals at roundabouts and current practice is to discourage its use.

Indirect or Direct Signal Control

Indirect Signal Control – where the signals are situated on a roundabout approach some distance away from the roundabout entry so that the roundabout continues to operate under normal roundabout priority control. There is no control over the circulating traffic. Where this control is provided it may include one or more roundabout entries (refer to Figure C3.1).

This form of operation is similar to the roundabout metering signals described in Section 7.1 that currently operates at the Point Lewis Rotary in Perth. It should be noted that in the UK three aspect signals are used for roundabout metering (amber, red, green) whereas in Australia two-aspect signals are used (amber, red, (blank)). This avoids the potential of drivers seeing the green signal and driving through the roundabout without paying attention to the Roundabout Give Way controls.



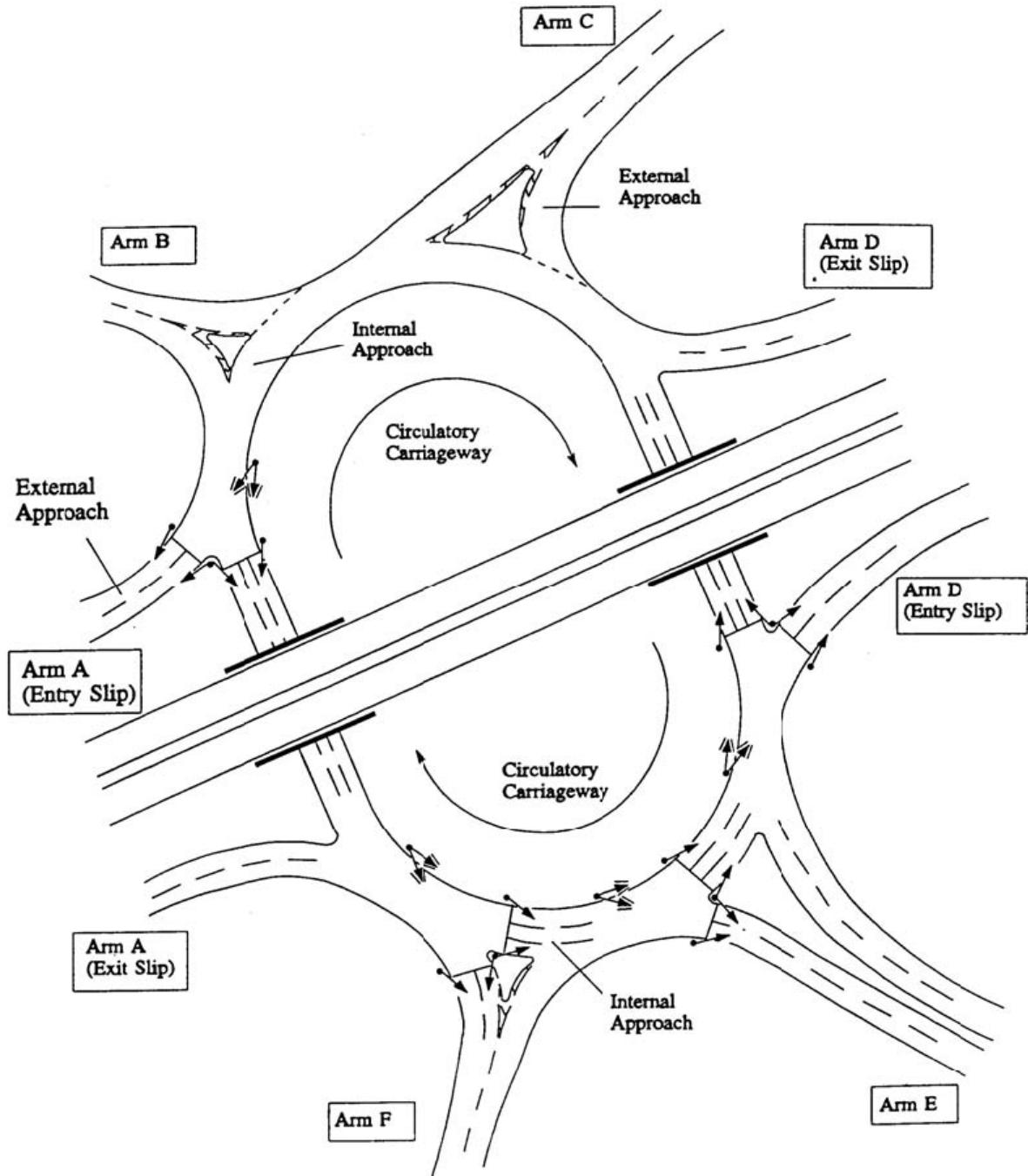
Source: (Highways Agency, 2004)

Figure C3.1 – Indirect Signal Control in the UK

Direct Signal Control – where signal control is provided at the junction of a roundabout entry with the circulating roadway (refer to Figure C3.2). This form of signal control has been implemented in Bunbury at the Eelup Rotary. Where this control is provided it may include:

- All entries to the roundabout (fully controlled).
- Only some of the roundabout approaches (partially controlled).

Direct signal control is more suited to large roundabouts where storage space is available for traffic to stop within the circulating roadway between the departure and entry legs of the roundabout. Where direct signal control is provided this may need to be accompanied with widening of approaches and/or the circulating roadway approaches at the signals to increase capacity or storage.



Source: (Highways Agency, 2004)

Figure C3.2 – Direct Signal Control in the UK

The direct signal control phasing sequence is able to operate to minimise lost time (generally anti-clockwise phasing). Phasing at a four-leg roundabout could allow opposite external approaches to run concurrently (refer to Figure 6.5) which would allow the through and left turning vehicles to depart the roundabout without stopping within the circulating roadway. The right turning vehicles would need to stop at the circulating roadway approach to the signals. This operation would provide similar safety benefits to fully controlled right turn movements at a conventional signalised intersection.

APPENDIX A

Examples of Roundabouts with more than Four Legs



Figure A.1: Example of a Single-lane Roundabout with Five Legs, Burpengary, QLD

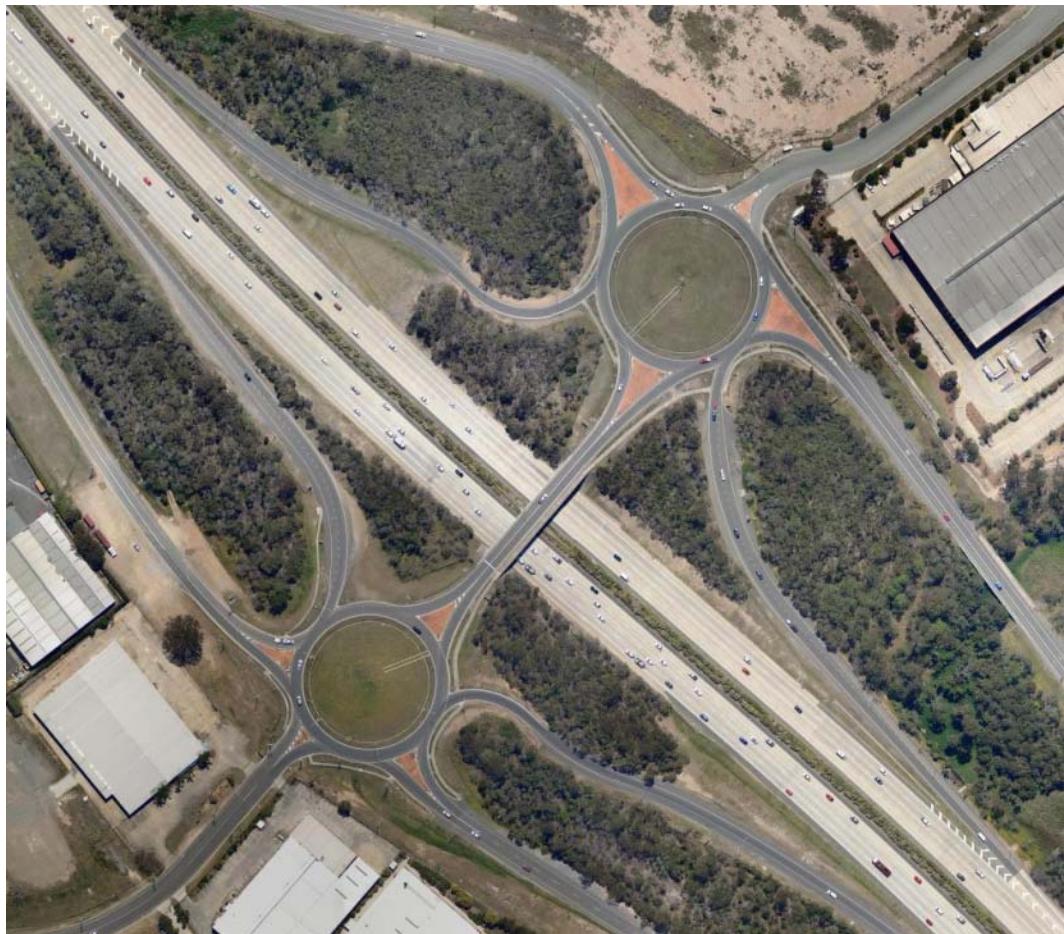


Figure A.2: Example of Two Single-lane Roundabouts with Six Legs Each Ormeau, Qld



Figure A.3: Example of Two Multi-lane Roundabouts with more than Four Legs

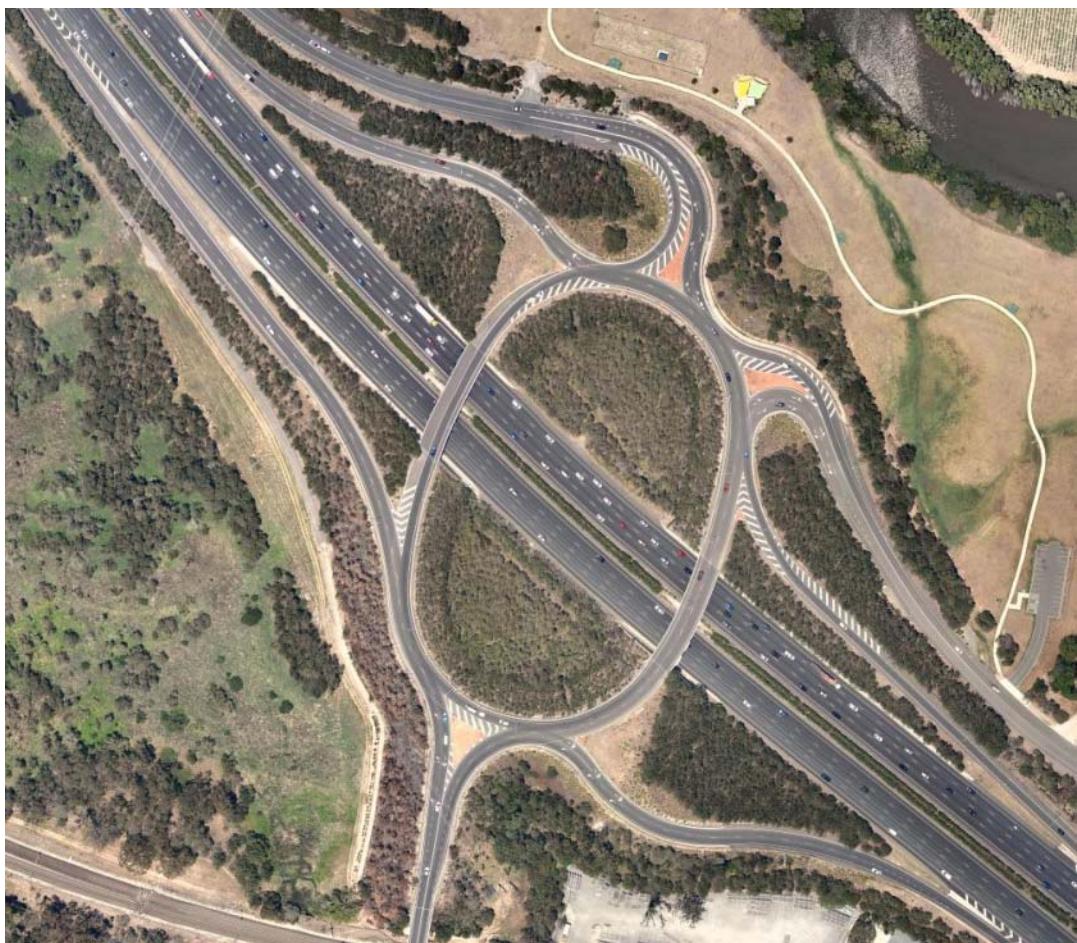


Figure A.4: Example of a Multi-lane Roundabout with more than Four Legs

APPENDIX B

Examples of Roundabouts with more than Two Circulating Lanes



Figure B.1: Example of 3-lane Roundabout in Victoria (Dandenong-Frankston Rd (Dandenong Valley Hwy) / Thompsons Rd. Carrum Downs)



Figure B.2: Example of 3-lane Roundabout in Victoria (Boundary Rd / Governor Rd, Braeside)

APPENDIX C

**Case Study: Eelup Rotary - Designing a Roundabout to Accommodate Large
Multi-combinational Vehicles**

Background

Prior to signalisation, the Eelup Rotary in Bunbury had an extremely poor crash record (albeit the vast majority of crashes were property-damage only) and was frequently congested during the peak periods. The major problem identified was that large multi-combinational vehicles struggled to “pick a gap” in the circulating traffic stream because of the high traffic volumes and high circulatory speeds. The large central diameter of 180m contributed directly to the high circulatory speeds. Figure C.1 shows the roundabout prior to upgrading.



Figure C.1: Eelup Rotary in 2011 prior to Upgrading

Design Proposals

An initial proposal to upgrade the roundabout had considered constructing a smaller roundabout within the existing central island in order to reduce the circulatory speeds. However, this would not have provided sufficient capacity and did not address the issue of truck drivers being able to “pick a gap” in the high circulatory flow.

A decision to signalise the roundabout was made based on the ability to utilise the existing pavement area effectively as well as taking advantage of the large internal storage area to store turning traffic. In addition, this catered well for future east-west grade separation plans. In 2011 construction commenced to upgrade the roundabout to a signalised roundabout. The main approaches were flared to three lanes and the circulating roadway was widened to three lanes in three of the four quadrants. In addition, left-turn slip lanes were provided for three of the four movements. The upgraded “roundabout” is shown in Figure C.2.



Figure C.2: Eelup Rotary in 2014 after Upgrading

Current crash records indicate a substantial reduction in the number of crashes and congestion during peak periods, including peak holiday long-weekend periods has largely been eliminated.

One of the key factors for the success of this roundabout was recognising the need to get drivers into the correct lanes prior to the roundabout. This was achieved using overhead advance direction signing, supplemented with pavement markings indicating destinations.

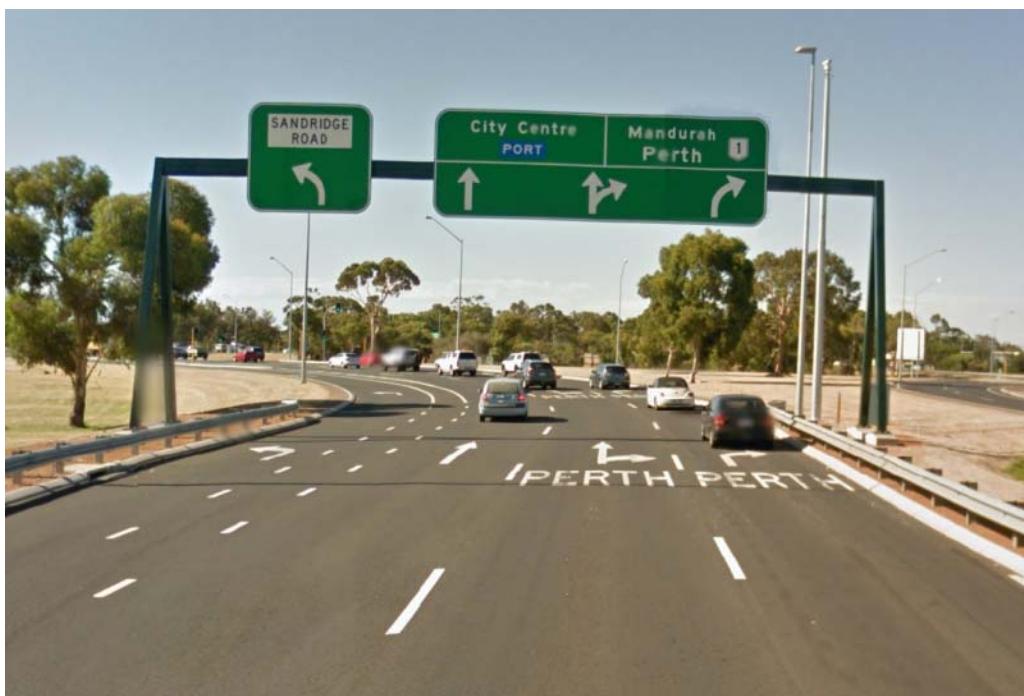


Figure C.3: Eelup Rotary showing Overhead Advance Direction Signs and Supplementary Pavement Markings

APPENDIX D

**Case Study: Point Lewis Rotary – Partial Signalisation of a Roundabout using
Metering Signals**

Background

Prior to the installation of metering signals, Point Lewis Rotary on Mounts Bay Road / Riverside Drive, Perth experienced extreme congestion during the peak periods:

- During the a.m. peak period, traffic on the northern approach (main a.m. peak movement) was blocked by the lesser west-to-east traffic flows from the western approach. The resulting queues extended back to the Mounts Bay Road freeway off-ramp and sometimes backed up onto the northbound Mitchell Freeway as well.
- During the p.m. peak period, traffic on the northern approach was sometimes blocked by traffic backing up into the roundabout from the eastern downstream exit, which leads onto the freeway.
- The existing geometry provided for slip lanes for the west-to-north as well as east-to-west movements. There were limited opportunities for further geometric improvements to address the capacity issues.

Figure D.1 shows the layout of the roundabout prior to the installation of the metering traffic signals.

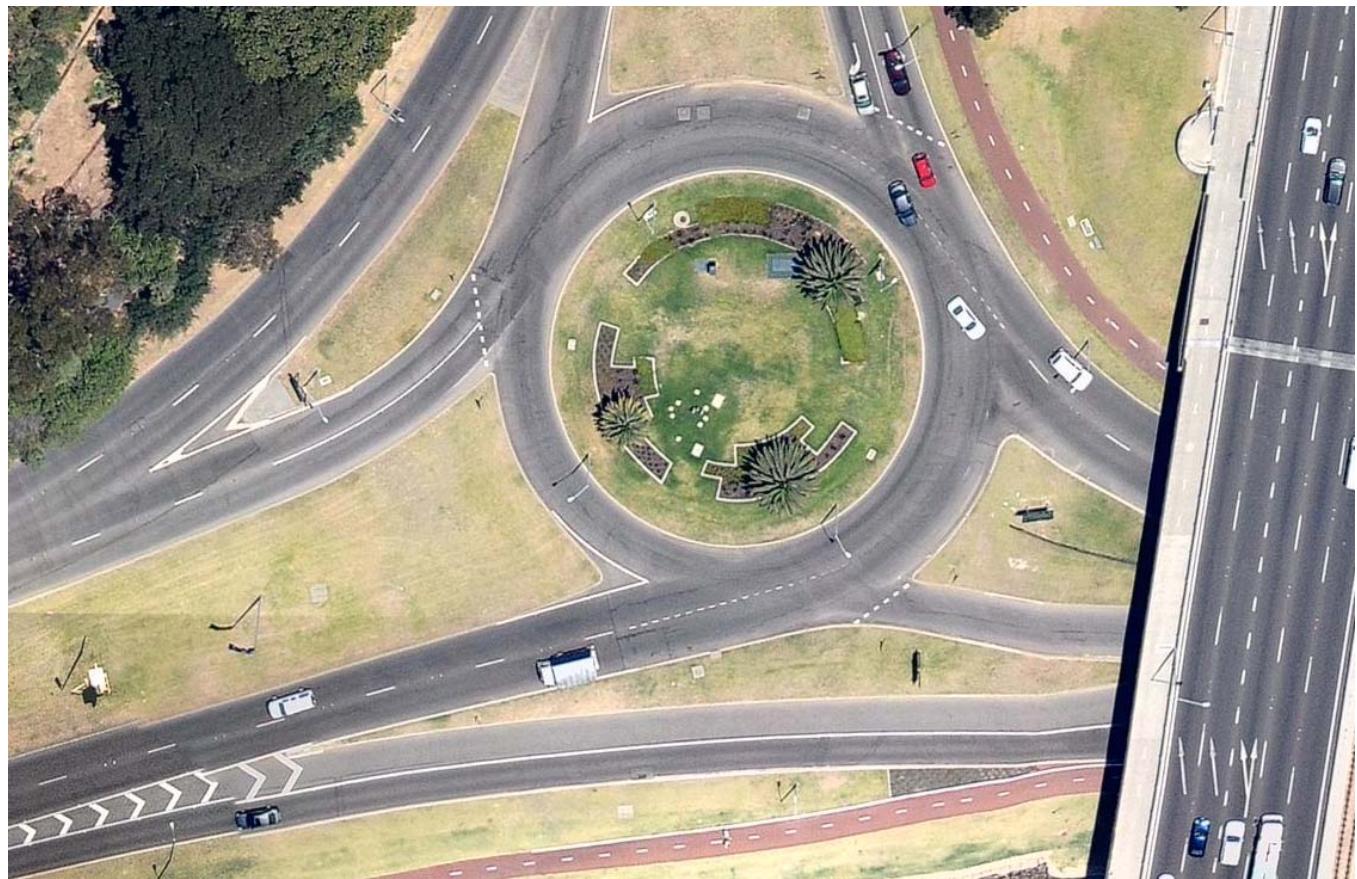


Figure D.1: Point Lewis Rotary prior to Installation of Roundabout Metering Signals

Design proposal

The implemented solution consisted of installing roundabout metering signals on the western approach. These are activated either by the traffic queued on the northern approach or by traffic backing up from the freeway on the eastern exit. The current layout is shown in Figure D.2. The STOP line is located a minimum of 19m from the roundabout hold line.

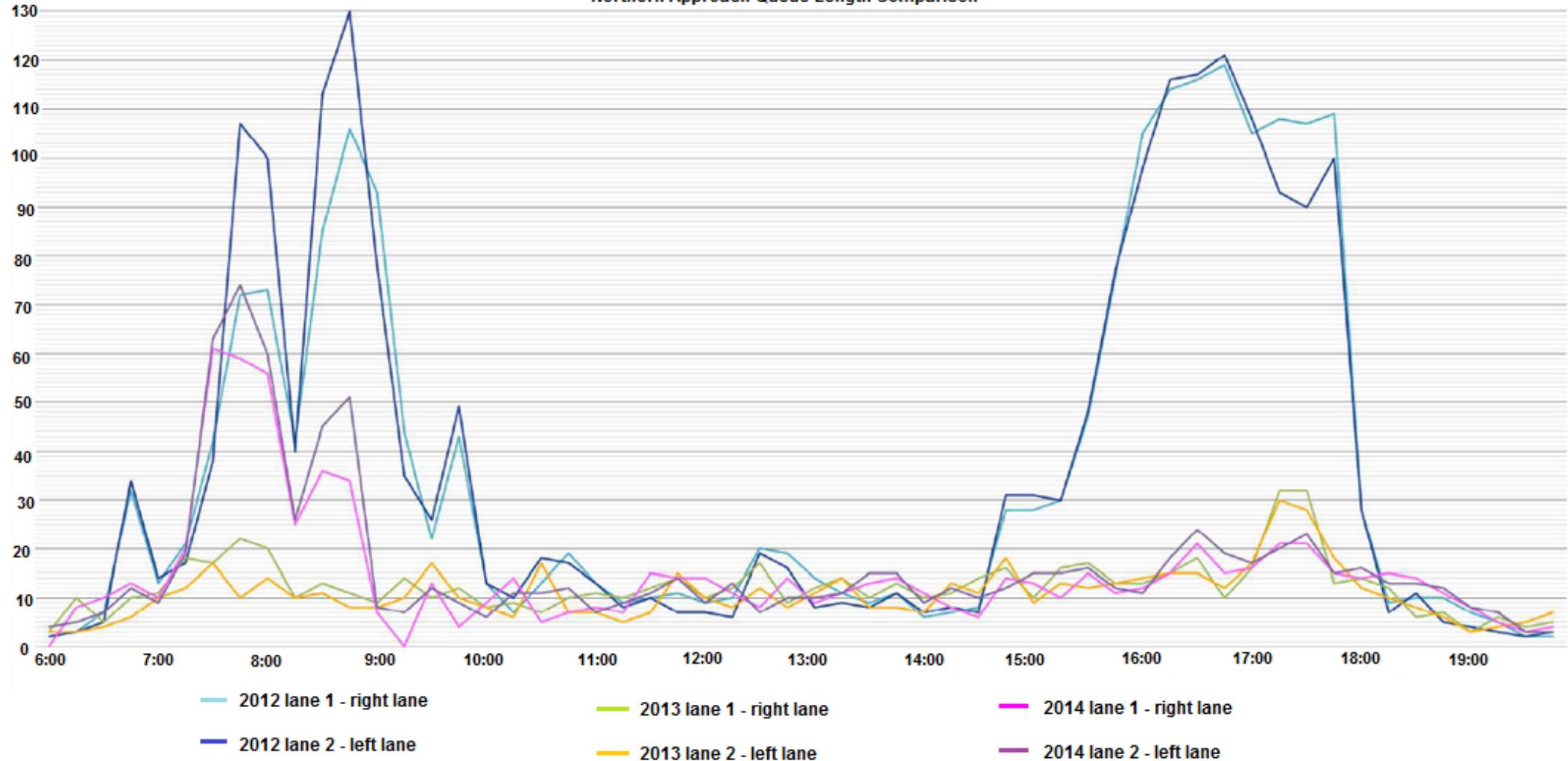


Figure D.2: Point Lewis Rotary after Installation of Roundabout Metering Signals

Post Implementation Results

Figure D.3 shows the maximum queue lengths on the northern approach, as measured in 2012, 2013 and 2014. The morning maximum queue lengths have decreased by over 40% from 2012 to 2014. The 2014 afternoon peak maximum queue lengths have decreased in size significantly; the maximum queue length is approximately 20% of the size of the 2012 afternoon peak maximum queue length. To date there has been virtually no negative feedback regarding the partial signalisation of this roundabout. Congestion has reduced significantly and by all accounts the implementation of roundabout metering may be considered a success.

Northern Approach Queue Length Comparison



Source: (Donald Veal Consultants, 2014)

Figure D.3: Point Lewis Rotary – Northern Approach (Lanes 1 & 2) – Maximum Queue lengths for 2012, 2013 and 2014

APPENDIX E

Intersection Control Options Checklist Pro-forma

Intersection Control Options Checklist

This table provides summary information to ensure critical issues are considered in making the recommendation. This is relevant to control options for arterial road intersections e.g. options for either traffic signals or a roundabout.

The table would generally be applicable to an intersection upgrading proposal or for intersection controls being part of a widening or duplication proposal. Where further detail is provided in the accompanying report, cross referencing should be provided.

| Project / Site: | | | | File Ref: |
|---|--|--|-----------------------------------|------------------|
| Local Government Authority: | Region: | | | |
| Item | Option 1 – Indicate Form of Control | Option 2 – Indicate Form of Control | Comment / Report Reference | |
| Road Environment | | | | |
| • Rural or inner/outer urban, adjacent land use, speed environment etc. | | | | |
| • Space, topography, design issues etc. | | | | |
| Road User Needs (if applicable) | | | | |
| • Pedestrians | | | | |
| • Bicycles | | | | |
| • Trucks | | | | |
| • Public transport | | | | |
| Traffic Management Considerations | | | | |
| • Route strategies – eg signal linking | | | | |
| • Road hierarchy, local access etc. | | | | |
| • Basis of design volumes / design year | | | | |

| Intersection Operational Performance | AM Peak | Off Peak | PM Peak | AM Peak | Off Peak | PM Peak | Traffic Signal Warrants met? – Y / N | |
|---|----------------|-----------------|----------------|----------------|-----------------|----------------|---|--|
| • Level of Service | | | | | | | | |
| • Degree of Saturation | | | | | | | | |
| • Queues | | | | | | | | |
| Analysis of Safety Performance | | | | | | | | |
| • Casualty crashes saved / year | | | | | | | | |
| Economic Evaluation | | | | | | | | |
| • Estimated cost | | | | | | | | |
| • Economic value of crashes saved | | | | | | | | |
| • Economic value of operational delays | | | | | | | | |
| • BCR | | | | | | | | |
| Consultation | | | | | | | | |
| • Community / LGA comments | | | | | | | | |

