University of Southern Queensland
Faculty of Engineering and Surveying

EVALUATION OF THE CAPACITY OF SIGNALISED TWO LANE ROUNDABOUTS

A dissertation submitted by

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ABSTRACT

There has been ever increasing demand in the signalisation of roundabouts with the intention of improving the capacity and safety of the intersection. The signalisation may be incorporated to reduce reliance on gap acceptance in heavily saturated conditions, control the dominance of a singular heavy leg demand, improve safety for cyclists and pedestrians or control all entry flows into the roundabout intersection.

This report evaluates the capacity of two lane signalised roundabouts under saturated conditions. Computer models were developed in LinSig and Excel to calculate the effective capacity of the intersections up to a level of service F. Models were developed based on differing variables such as inscribed diameters, queue discharge headways, phase sequences and signal cycle times. Relationships between the variables and the impact they had on the capacity of the signalised roundabout intersection were evaluated. The variables used in the capacity models were based on field research conducted under Australian driving conditions and research gathered from around the world. These models were then compared to un-signalised capacities calculated from previous research across the world.

The conclusions from the project has found that a signalised roundabout using the standard phasing technique is a viable option in replacing an existing un-signalised roundabout that is failing to cater for capacities. This is compounded if the intersection has a high percentage of right turn movements, pedestrian flows and is located in an urban environment. The installation of signals to an existing roundabout is deemed to be a cost effective solution in improving capacities.

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CERTIFICATION

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

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

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GLOSSARY

Term	Definition
acceleration (m/s^2)	The act of accelerating; increase of speed or velocity
all-red interval (s)	The time interval between when all signals are under a red phase.
capacity (veh/hr)	The maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions.
carriageway	one of the two sides of a motorway/highway where traffic travels in one direction only usually in two or three lanes
cycle time (s)	The total time for a signalised intersection to complete all its phases.
deflection	The deviation of a vehicle from conducting a straight through movement
delay	The period of time one is stopped from completing their desired movement
gap	The time interval between the departure at a point of one vehicle and the arrival at the same point of the next vehicle.
geometric delay	The distance one is forced to conduct from completing their desired movement
giveway	The act of slowing down or stopping to check or stop for a an oncoming vehicle at an intersection.
grade separated interchange	An intersection that separates the two conflicting roads vertically so they are free to complete their desired movement without the act of giving way.
headway	The distance in time or space that seperates two vehicles travelling the same route
intersection at grade	An intersection where carriageways cross at a common level.
lane saturation	The volume of traffic that occupies the lane at present time divided by the total capacity the lane is able to occupy.
level of service	A qualitative measure describing operational conditions within a traffic stream, and their perception by motorists and/or passengers.
LinSig	A computer software program developed in the UK to determine the capacities of intersections.
passenger car equivalent (pce)	The equivalent ratio that a mode of transport has on the capacity of the intersection compared to a single car.
passenger car unit (pcu)	The equivalent ratio that a mode of transport has on the capacity of the intersection compared to a single car.
pedestrian	A person travelling on foot
phase	A singular element that is part of a cycle.

queue	A line of waiting people or vehicles
red clearance time (s)	The time in seconds relating to the clearance between two entering vehicles into an intersection from two opposing legs.
roundabout	A road junction at which traffic moves in one direction round a central island to reach one of the roads converging on it.
rural	Of relating to, or characteristic of the country
through lane	A lane provided for the use of vehicles proceeding straight ahead.
traffic	The passage of people or vehicles along routes of transportation.
traffic circle	Large roundabouts that allowed entering traffic the right of way.
urban	Of relating to, or located in a city.
yield	Refer to giveway

1. INTRODUCTION

Roundabouts have been adopted throughout the world to govern the traffic flow at intersections for variable traffic demands. They generally consist of four approaching legs of traffic, that give way to circulating traffic navigating around a central island (usually circular).

Roundabouts can be used in many different situations within a road network. They can be adopted in both low and high traffic volumes with the measures to increase safety and improve capacity of an intersection. A few key features determine what specific type of roundabout is needed, these features include:

- traffic demand
- size
- environment

These factors impact on the design characteristics such as the speed of entry and exits, the diameter of roundabout, number of circulating lanes and ability to service daily traffic flows. The Federal Highway Administration (FHWA, 2010) class roundabouts into six main categories, these include:

1. Small residential roundabouts
2. Compact urban roundabouts
3. Urban single lane roundabouts
4. Rural single lane roundabouts
5. Urban two lane roundabouts
6. Rural two lane roundabouts

There has been ever increasing demand in the signalisation of roundabouts with the intention of improving the capacity and safety of the intersection. The signalisation may be incorporated to reduce reliance on gap acceptance in heavily saturated conditions, control the dominance of a singular heavy leg demand, improve safety for cyclists and pedestrians or control all entry flows into the roundabout intersection.

This report will examine the capacity for urban and rural two lane signalised roundabouts. LinSig and excel computer software will be used to determine the capacities of signalised roundabouts under a certain signal phase. Traffic flow characteristics will be input into the LinSig and excel models based on an Australian analytical approaches with supportive research based from around the world.

These capacities will be compared to conventional un-signalised roundabouts to determine if the signalisation of a roundabout is an effective means to increase the capacity of the intersection.

1.1 Problem Statement

The research undertaken in this report has been developed in response of replacing existing roundabouts that are failing to provide an adequate level of service to increasing traffic demands. The normal progression in Australia has been to replace non-performing roundabouts with a typical signalised intersection or to a greater extent grade separated interchange. This incurs costs of removing the existing roundabout as well as its footprint and reshaping the intersection to the desired signalised intersection geometry.

This report will examine whether installing (retro-fitting) signals to an existing un-signalised roundabout will help improve the capacity of the roundabout and in turn improve the life span of the intersection at a more cost effective solution than replacing with a new signalised intersection layout.

1.2 Project Objectives

- A complete review of local and overseas researches on traffic flow characteristics at un-signalised and signalised roundabouts.

- Develop traffic capacity models with various radii using Excel and LinSig, LinSig is a computer software programme that assesses the design of signalised roundabouts and intersections.

- Apply uniform traffic flows to each leg of the intersection and assess the impact of traffic flows on level of service.

- Establish relationships between design parameters (radius, cycle times, queue discharge headways) and the capacity of a signalised roundabout.

- Compare the traffic flow capacity of signalised roundabouts to conventional un-signalised roundabout designs.

2. BACKGROUND

This section aims to provide background information based from research sought globally on the history, research and implementation of roundabouts around the world. The information from the background will be used as the basis in the required aims and hypotheses of the project.

2.1 Un-signalised Roundabouts

'Traffic circles have been part of the transportation system in the United States since 1905, when the Columbus Circle designed by William Phelps Eno opened in New York City' (FHWA 2000, p 2). These traffic circles were unlike modern roundabouts today as they gave entering traffic the right of way, thus causing the circulating traffic to give way. This developed numerous problems with roundabouts which involved locking up of traffic around the central island, aiding high speed entry and the merging and weaving of vehicles leading to severe crashes.

After numerous traffic mishaps within these traffic circle intersections in the United States, the Americans decided to abandon the traffic circle designed intersections. The British decided to continue to develop and refine the design of these traffic circles and came up with the mandatory give way rule that allowed the development of modern roundabouts to continue to become safe and effective intersections.

'In 1966, the United Kingdom adopted mandatory "give-way" rule at circular intersections, which required entering traffic to give way, or yield, to circulating traffic' (FHWA 2000, p 2). By adopting this rule, roundabouts became free flowing as it did not allow vehicles to enter the roundabout until there was a sufficient gap in the circulating traffic.
The differences of modern roundabouts from the traditional traffic circles include:

- Roundabouts require entering drivers to give way to all traffic within the roundabout.
- Roundabouts allow the inner lane of a multi lane roundabout to exit.
- Deflection on entry is used to maintain low speed operation in roundabouts.
- Pedestrians are permitted from the central island of a roundabout.
- Modern roundabouts are much smaller in diameter than traffic circles.

The United States of America finally adopted the design of the modern roundabout in 1990 in Summerlin, Las Vegas. Since then USA have adopted the modern roundabout and as of December 2009 the number of modern roundabouts in the USA was approximately 2,300.

In 1984, the French government adopted the mandatory give way rule to circulating traffic and as of mid-1997 there are about 15,000 modern roundabouts in France (Jacquemart 1998). In addition to their popularity in Great Britain and France, roundabouts are very common in Germany, Switzerland, Spain and Portugal. 'Outside of Europe the modern roundabout is a standard feature in Australia and it is becoming more common in New Zealand, South Africa and Israel' (Jacquemart 1998, p 11).

2.1.1 Australia

Roundabouts were adopted extensively during the 1980's in Australia due to the benefit of less severe crashes and a relatively low crash rate between motor vehicles compared to other intersections. The three main factors which have led to the replacement of roundabouts to a signalised intersection are as follows:

1. Capacity issues in saturated flow periods.
2. Safety for Cyclists
3. Safety for Pedestrians

Capacity issues arise in saturated conditions due to limited gap space for entering vehicles. This is compounded when there is a dominant leg which creates large queue lengths for the opposing entering traffic. Capacity issues will be discussed more in depth in the next section of the report.

Austroads (2011) states that in multi lane roundabouts the safety for cyclists is markedly less than that of motor vehicles. A French study (Alphand, Noelle and Guichet 1991) determined that there was twice as many injury crashes for cyclists at roundabouts than at signalised intersections.

A study in New South Wales by Robinson (1998) found:

- 6% of those injured at cross sections were cyclists compare with 18% at roundabouts.
- At non-metropolitan roundabouts, 32% of those injured in 2-party crashes were cyclists.
- Cyclist were responsible for 16% of the crashes in which they were involved.

'Under *National Transport Commission, (Road Transport Legislation, Australian Road Rules) Regulations 2006* vehicles leaving a roundabout are not obliged to give way to pedestrians' (Austroads 2011, p 48). This makes roundabouts inappropriate when there is a high level demand of pedestrians.

These factors have influenced a trend particularly in the United Kingdom to adopt signalisation at existing roundabouts to improve the above mentioned problems.

2.2 Signalised Roundabouts

'Signalisation of roundabouts was first experimented in 1959 in the United Kingdom (UK) to prevent circulating traffic from blocking entering traffic during peak periods' (DFT, 2009). Although with the introduction to the mandatory give way rule in 1966, which allowed un-signalised roundabouts to become more effective, they still had issues arising from unbalanced flows causing limited gap space for entering vehicles.

'There has been a rapid increase in the installation of signal controlled roundabouts in the UK since the early 1990s' (DFT, 2009). Table 2.1 shows a comparison from 1997 & 2006 of the reasons for signalisation on roundabouts, taken from 49 authorities on 161 signalised roundabouts within the United Kingdom.

Table 2.1 – Comparison of Surveys 1997/2006 (DFT, 2009)

Trends in signalisation of roundabouts	1997 (%)	2006 (%)
Location		
Urban (50 or 60 km/h limit)	55	62
Rural (70 km/h or greater limit)	45	38
Reasons for signalisation		
Queue Control	70	80
Increased capacity	67	70
Accident reduction	60	72
UTC linkage	27	15
Pedestrians/cyclists	-	38
Other	24	-
Type of Control		
Fully signalised	35	48
Pedestrians/cyclists facility	34	32
Full-time control	64	86
Appraisal tools		
TRANSYT	-	83*
LinSig	-	33*
VISSIM	-	Low
Paramics	-	Low
* Note: Some authorities use both packages		

The data received from the comparison show a greater trend towards full time signal control to improve queue control, increase capacity and improve safety.

Safety of pedestrians and cyclists through roundabouts has been a major issue around the world with various designs used to enable these movements throughout modern roundabouts. Signalisation of roundabouts provides an effective and safe route for both pedestrians and cyclists which have led to the increase in signalisation of roundabouts.

This report will analyse the impact signalisation has to the capacity of a two lane roundabout.

3. LITERATURE REVIEW

This literature review will detail the necessary information to ensure the variables affecting the capacity of roundabouts are understood and accounted for. This information will provide the structure for the variable inputs into the computer software modelling to determine the capacity of a two lane signalised roundabout.

This section will first provide general information about roundabouts and their key features. It will then look into the important features of signalisation and traffic flow characteristics that will impact on determining the capacity of a two lane roundabout. Finally it will describe the features and limitations of the computer software modelling used in determining the project objectives.

3.1 Un-signalised roundabouts

3.1.1 General

'Roundabouts are circular intersections with specific design and traffic control features. These features include give-way control of all entering traffic, channelised approaches and appropriate geometric curvature to ensure that travel speeds on the circulatory roadway are typically less than 50km/h' (FHWA 2000, p 5). Roundabouts can be classed into six main categories as shown in Table 3.1 below.

Table 3.1 – Design characteristics for each six roundabout categories (FHWA 2000, p 13)

Design Element	Mini-Roundabout	Urban Compact	Urban Single-Lane	Urban Double-Lane	Rural Single-Lane	Rural Double-Lane
Recommended maximum entry design speed	25 km/h (15 mph)	25 km/h (15 mph)	35 km/h (20 mph)	40 km/h (25 mph)	40 km/h (25 mph)	50 km/h (30 mph)
Maximum number of entering lanes per approach	1	1	1	2	1	2
Typical inscribed circle diameter	13m to 25m (45ft to 80ft)	25m to 30m (80ft to 100ft)	30m to 40m (100ft to 130ft)	45m to 55m (150ft to 180ft)	35m to 40m (115ft to 130ft)	55m to 60m (180ft to 200ft)
Splitter island treatment	Raised if possible, crosswalk cut if raised	Raised, with crosswalk cut	Raised, with crosswalk cut	Raised, with crosswalk cut	Raised and extended, with crosswalk cut	Raised and extended, with crosswalk cut
Typical daily service volumes on 4-leg roundabout (veh/day)	10,000	15,000	20,000	40,000 to 50,000	20,000	40,000 to 50,000

This report will be focused on rural two lane roundabouts. The key geometric elements of a rural two lane roundabout are shown in Figure 3.1.

Roundabouts introduce an entry curve to slow entering traffic down to give-way to circulating traffic. The entry and exit curves are separated by a raised median called a splitter island, which is designed to deflect and slow entering traffic in conjunction with the entry curve. The vehicles then enter the roundabout when a sufficient gap is presented, than travel within the circulating carriageway until they reach their desired exit.

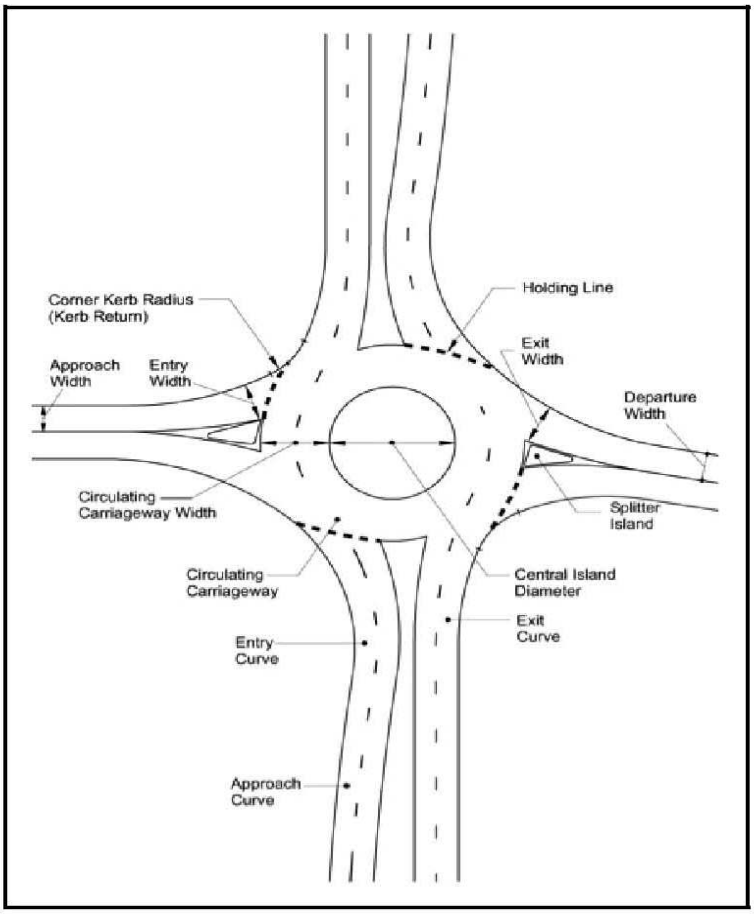


Figure 3.1 – Geometric elements of a roundabout. (Austroads 2007, p 36)

Table 3.2 – Descriptions of key roundabout features.

Feature	Description
Approach Curve	The approached curve is used to slow the operating speed of vehicles coming from a high speed environment.
Entry Curve	The entry curve is used to deflect and slow entering vehicles to an appropriate speed to safely circulate the roundabout.
Entry Width	The entry width is the width of the entry where it meets the circulating carriageway.
Holding Line	The holding line is pavement marking that defines where the vehicles have to give way to the circulating traffic. It is generally marked along the inscribed circle.
Circulating Carriageway	The circulating carriageway is a curved path used by vehicles to travel around the central island. This is defined by painted line marking.
Circulating Carriageway Width	Defines the roadway width for vehicle circulation around the central island. The circulating carriageway width has to be wide enough to accommodate the largest design vehicles turning path.
Exit Width	The exit width is the width of the exit where it meets the circulating carriageway.
Exit Curve	The exit curve is generally bigger/flatter than the entry curve to allow vehicles to exit at a faster speed to improve traffic capacity and flow.

3.1.2 Capacity

The Highway Capacity Manual (HCM, 2010) defines the capacity of a facility as 'the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions.'

The capacity of a roundabout depends on two major principles:

- The effect of traffic flow and driver behaviour,
- The effect of roundabout geometry.

3.1.2.1 Effect of traffic flow and driver behaviour

Different driver behaviours are experienced around the world. Some drivers in certain countries may approach a roundabout at a higher speed or accept a smaller gap upon entry into the roundabout, which has an impact on the capacity of the roundabout.

There are several effects of driver behaviour that are consistent across the world that have an impact on the capacity of a roundabout. The effects from driver behaviour on traffic flow are:

- Effect of exiting vehicles – The effect of exiting vehicles may have an impact on when the entering vehicle feels comfortable to enter the circulating carriageway. This effect is similar to a vehicle wishing to turn left into the lane a vehicle is exiting, the driver may not feel comfortable to exit until the vehicle is in the motion of turning even if the vehicle has indicated on turning left.
- Changes in effective priority – When the roundabout is under saturated conditions driver behaviour becomes more aggressive. Instead of entering traffic providing the required gap as to not disrupt the circulating traffic, the vehicles are more likely to forcefully enter requiring the circulating traffic to give way to the entering traffic.
- Origin to destination patterns – This has an impact if there is a heavy through or right turn movement from one leg. If there is continual traffic flow that is unimpeded from a downstream leg it will not provide sufficient gaps for entering traffic causing long delays and traffic queues from upstream legs.

The effects of driver behaviour can be so variable that it is difficult to model for capacities accurately based on computer software. Inputs for driver behaviour within computer software modelling should be based on extensive field testing on real life conditions with similar geographic conditions.

3.1.2.2 Effect of roundabout geometry

The geometry of a roundabout can have an impact on the capacity of a roundabout in the following areas:

- 'It affects the speed of vehicles through the intersection, thus influencing their travel time by virtue of geometry alone (geometric delay)' (FHWA 2010, p4-5).
- The larger the diameter of the roundabout provides more capacity within the circulating carriageway.
- The width of the circulating carriageway, entry widths and exit widths have an impact on the capacity and can govern the speed at which drivers feel comfortable to enter and navigate around the roundabout.
- 'It can affect the degree to which flow in a given lane is facilitated or constrained. For example, the angle at which a vehicle enters affects the speed of that vehicle, with entries that are more perpendicular requiring slower speeds and thus longer headways. Likewise, the geometry of multilane entries may influence the degree to which drivers are comfortable entering next to one another' (FHWA 2010, p4-5).
- 'It may affect the driver's perception of how to navigate the roundabout and their corresponding lane choice approaching the entry' (FHWA 2010, p4-5).

The capacity of a roundabout is mainly dependent on the amount of approaching lanes and circulating lanes. The capacity is also affected more subtly by entry curves, entry widths and lane widths. There has been extensive research done into the capacity of two lane roundabouts across the world. Generally it is found that the capacity of a two-lane roundabout is expected to be between 40,000 to 50,000 vehicles per day.

The percentage of heavy vehicles is also a major factor to the capacity. The higher the percentage the lower the capacity of the roundabout due to the slower travel and turning speeds through the roundabout.

Figure 3.2 shows research conducted by the Federal Highway Administration into the capacity of a two lane roundabout. The capacity forecast is based on simplified UK empirical regression methods that differ from Australia and USA methods of gap acceptance theory.

It identifies that the maximum entry flow reaches a maximum of 2400 veh/hr when there is no circulatory flow. On the contrary it shows that when the circulatory flow reaches approximately 3400 vehicle per hour, no vehicles are able to enter into the roundabout adding to the capacity.

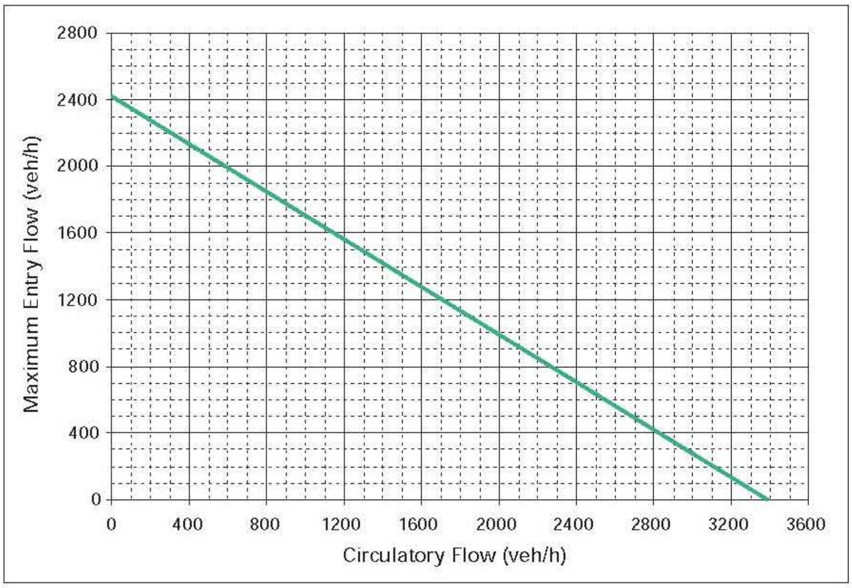


Figure 3.2 – Approach capacity of a two-lane roundabout (FHWA 2000, p 88)

The HCM (2010) defines the capacity of two lane roundabouts with two circulating flows as:

$$^{1}C_{e,R,pce} = 1{,}130e^{(-0.0007)\upsilon_{c,pce}} \tag{3.1}$$

$$^{2}C_{e,L,pce} = 1{,}130e^{(-0.00075)\upsilon_{c,pce}} \tag{3.2}$$

Where:

$C_{e,R,pce}$ = capacity of the right entry lane, adjusted for heavy vehicles (pc/hr),

$C_{e,L,pce}$ = capacity of the left entry lane, adjusted for heavy vehicles (pc/hr), and

$\upsilon_{c,pce}$ = conflicting flow rate (total of both lanes) (pc/hr).

[1] Right lane corresponds to left lane in Australia and UK.
[2] Left lane corresponds to right lane in Australia and UK.

Figure 3.3 has been developed based on these equations to produce the capacity estimates of single-lane and multilane entry capacities.

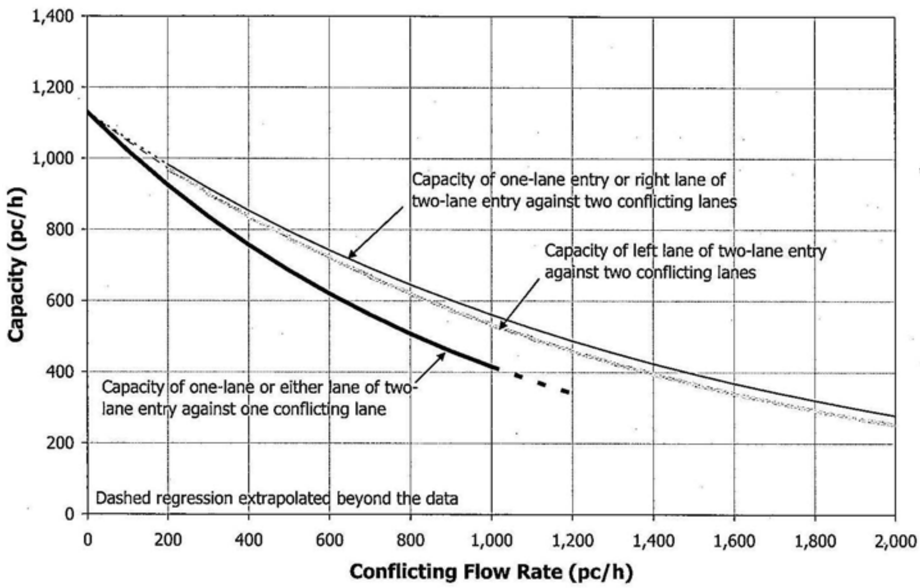


Figure 3.3[3] *– Capacity of Single-Lane and Multilane entries (HCM 2010, Exhibit 21-7)*

These findings represented in Figures 3.2 & 3.3 show the entering capacities for a leg into a roundabout against a conflicting circulating flow rate. This can make it hard when comparing the total capacity of the intersection to a signalised case. Tan (2001) determined a formula to assess the full capacity (Q_{fcr}) of a roundabout under fully saturated conditions. The formula is:

$$Q_{fcr} = 4F / \{1/\kappa + [\beta * R_h + 2R_r) + \alpha] * f\} \quad (3.3)$$

Where;

F = coefficient (represented in equation 3.4)

f = coefficient (represented in equation 3.4)

κ = lane entry factor, 2 lanes in entry = 1.4 – 1.6

β = circulating carriageway lane factor, 2 lanes in circulating carriageway = 0.6 – 0.8

α = determined from Figure 3.4 (L_{ba} is the distance between diverging point at exit and converging point at entry)

R_h = Ratio of through movements to all movements

R_r = Ratio of right turn movements to all movements

[3] Left lane corresponds to right lane and vice versa in Australia and UK.

Here we can see the effect the right turn movements have on the capacity of the roundabout. The entry capacity is affected by the right turn movements from the opposite entry lanes along with the through and right turn movement from the entry lanes on the right side of the entry.

Tan (2001) states that Swiss guide to roundabout design has determined the coefficients for F and f for fully saturated conditions based on the entry capacity researched in England, France and Switzerland (Q_e):

$$Q_e = F - Q_g * f \quad (3.4)$$

Where;

Q_g = conflicting flow

The Swiss guide calculates the coefficients F & f based on:

$$Q_e = \kappa[1500 - (8/9) * Q_g]$$

Therefore, $F = 1500$

$f = 8/9$

These coefficients are to reflect at saturated conditions.

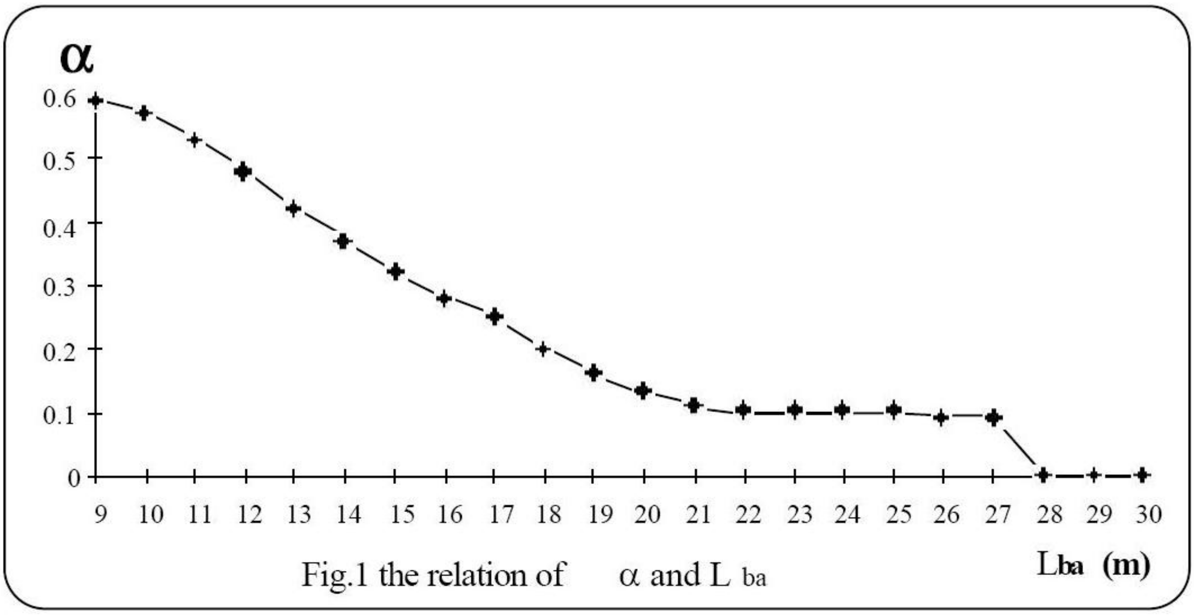


Figure 3.4 – The relation of α and L_{ba} (Tan 2001, Fig.1)

Pedestrians can reduce the entry capacity of a roundabout if they assert right-of-way on vehicles entering the roundabout. Worldwide there are different rules and regulations regarding the right-of-way of pedestrians in regards to roundabouts. In Australia vehicles are not obliged to give way to pedestrians upon exiting the roundabout according to the National Transport Commission.

Research by (Brilon, Stuwe, and Drews 1993) determined a reduction factor for pedestrians on the capacity for a two lane roundabout which is represented in Figure 3.5. This reduction factor can be used to compare capacities to signalised roundabouts which gives priority to pedestrians. This will provide similar intersection characteristics between un-signalised and signalised roundabouts.

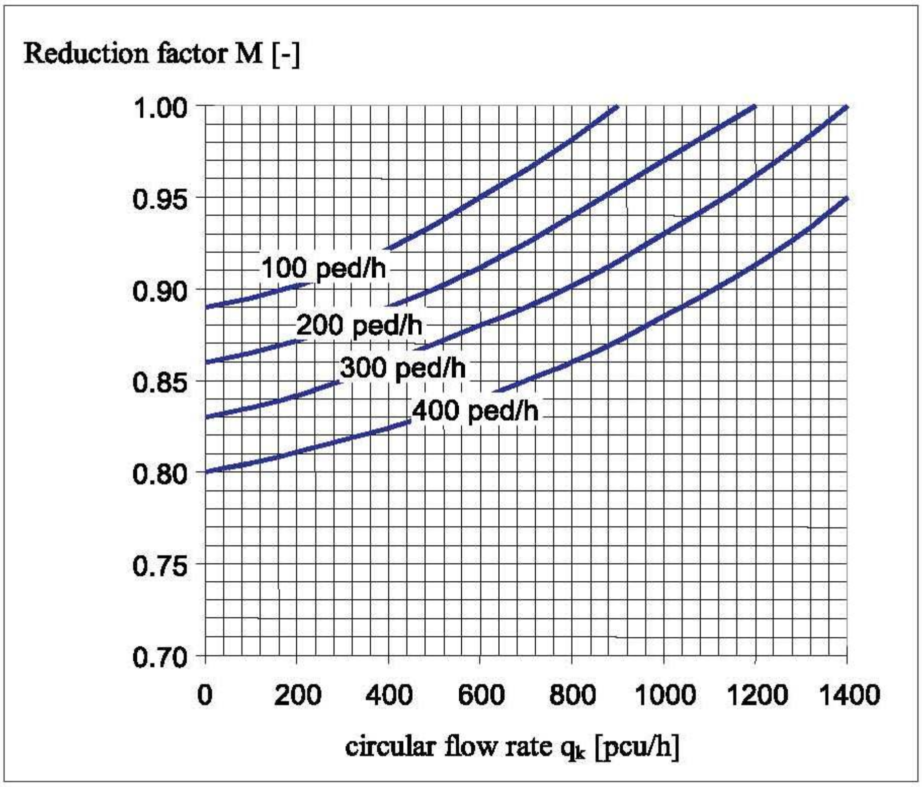


Figure 3.5 – Capacity reduction factor for a two lane roundabout assuming pedestrian priority. (Brilon, Stuwe, and Drews 1993)

All these factors have to be considered when determining the capacity of a roundabout. Each specific roundabout will have its own unique parameters due to geometry, driver behaviour and traffic fleet. To determine the most accurate capacities for a roundabout, all the inputs of these parameters should be based on research conducted to similar conditions that best relate to the designed roundabout examined.

3.2 Signalised Roundabouts

3.2.1 General

The geometric elements of a signalised roundabout are the same as the geometric elements of a standard un-signalised roundabout, accept with the addition of traffic signals and possible hold lines within the circulating carriageway. Hold lines within the roundabout are used when there is a high pedestrian and cyclist demand to allow traffic completing a U-turn to give way to crossing pedestrians and cyclists.

Shown in Figure 3.6 is a geometric layout of a proposed signalised roundabout without pedestrian and cyclist demand.

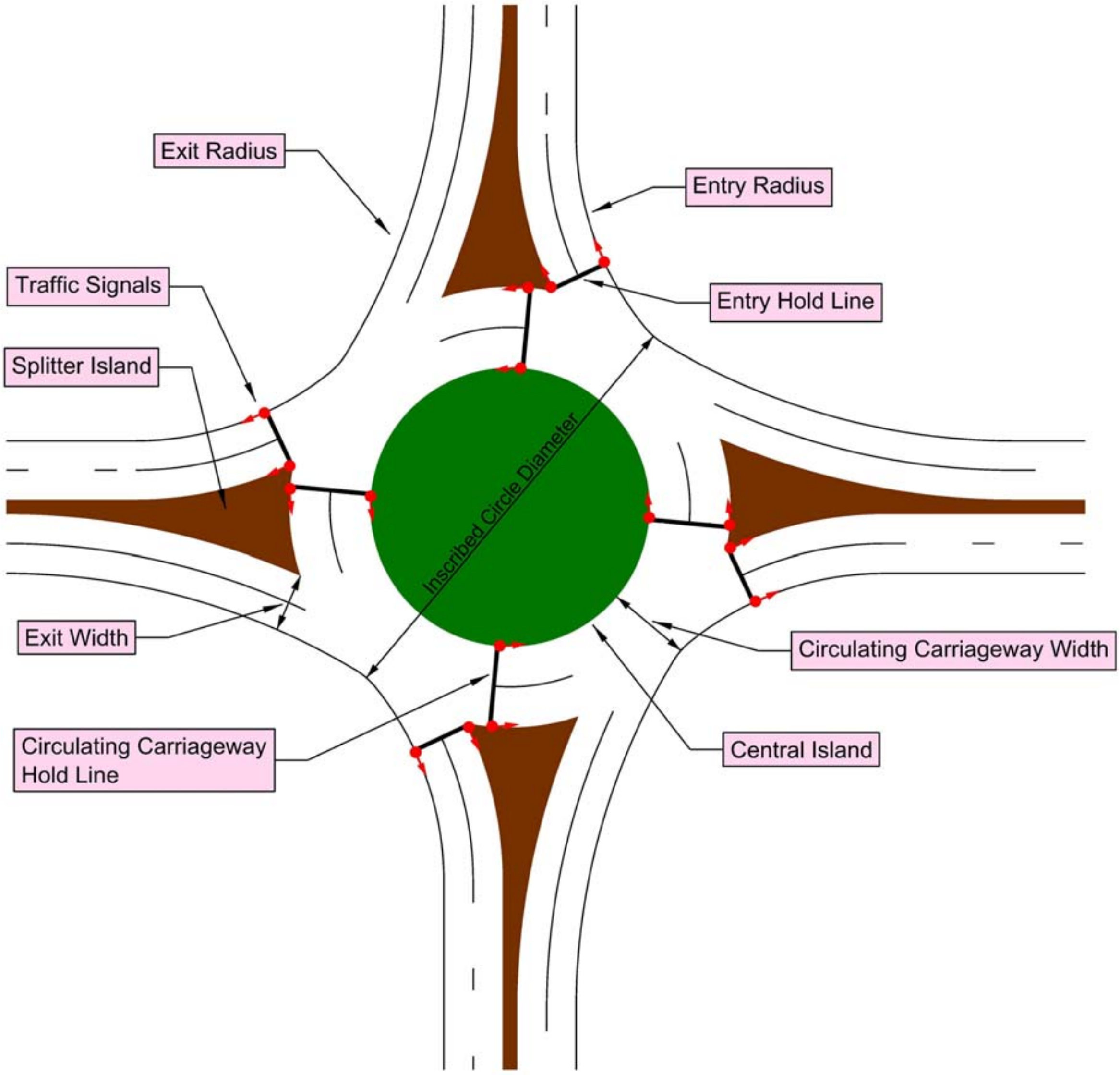


Figure 3.6 – Geometric elements of a signalised roundabout without pedestrian and cyclist demand

Figure 3.7 shows a typical configuration of a signalised roundabout with pedestrian and cyclist demand.

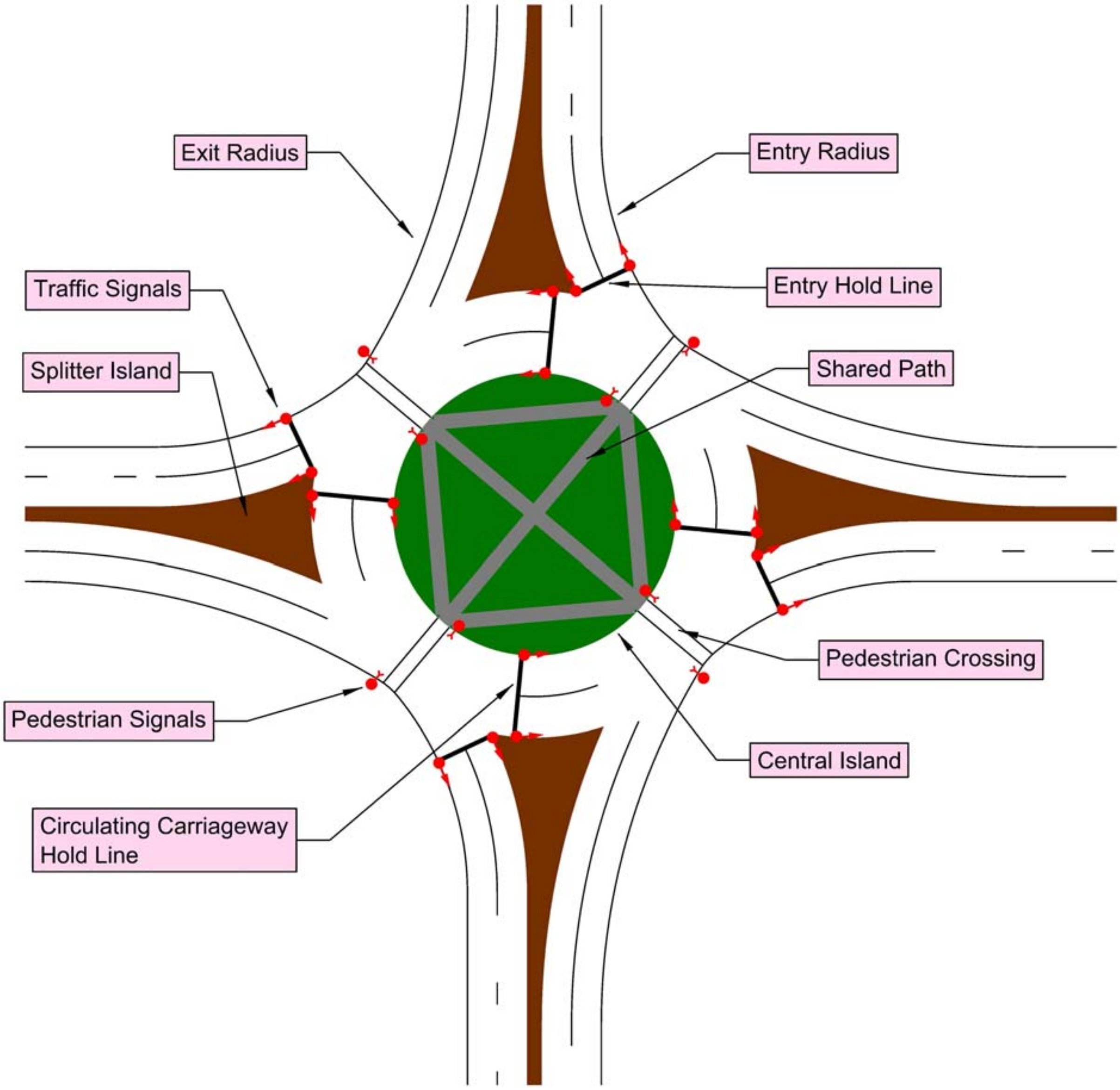


Figure 3.7 – Geometric elements of a signalised roundabout with pedestrian and cyclist demand

3.2.2 Signalisation and Phasing

The addition of signalisation adds another dynamic to the control of the intersection. It eliminates the need for gap acceptance and allows the ability to control phasing and also control the time of these phases to gain the best outcome for traffic flow around the intersection. It eliminates the dominance of a singular heavy demand and can cater safely for pedestrians and cyclists.

Shown below in Figures 3.8 and 3.9 is the general phasing structure used for signalised roundabouts in the United Kingdom. The entry lanes are represented by the letters B, D, F, H and the inner phase is represented by the letters A, C, E, G in Figure 3.7.

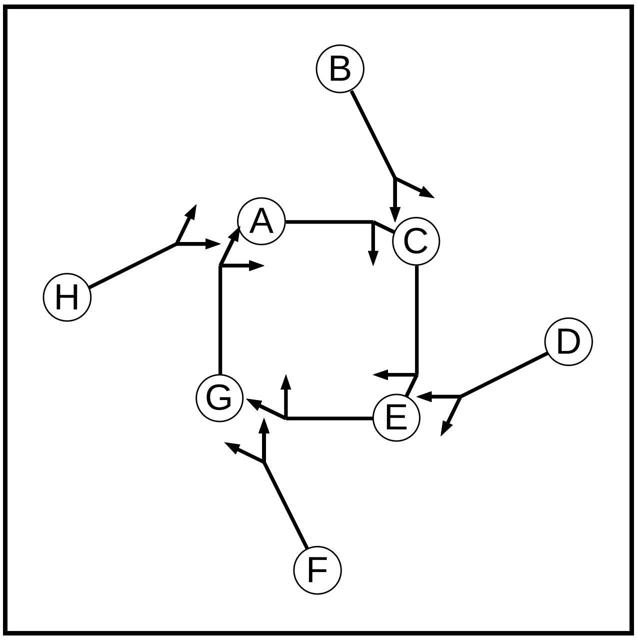


Figure 3.8 – General phasing structure of signalised roundabouts in the United Kingdom

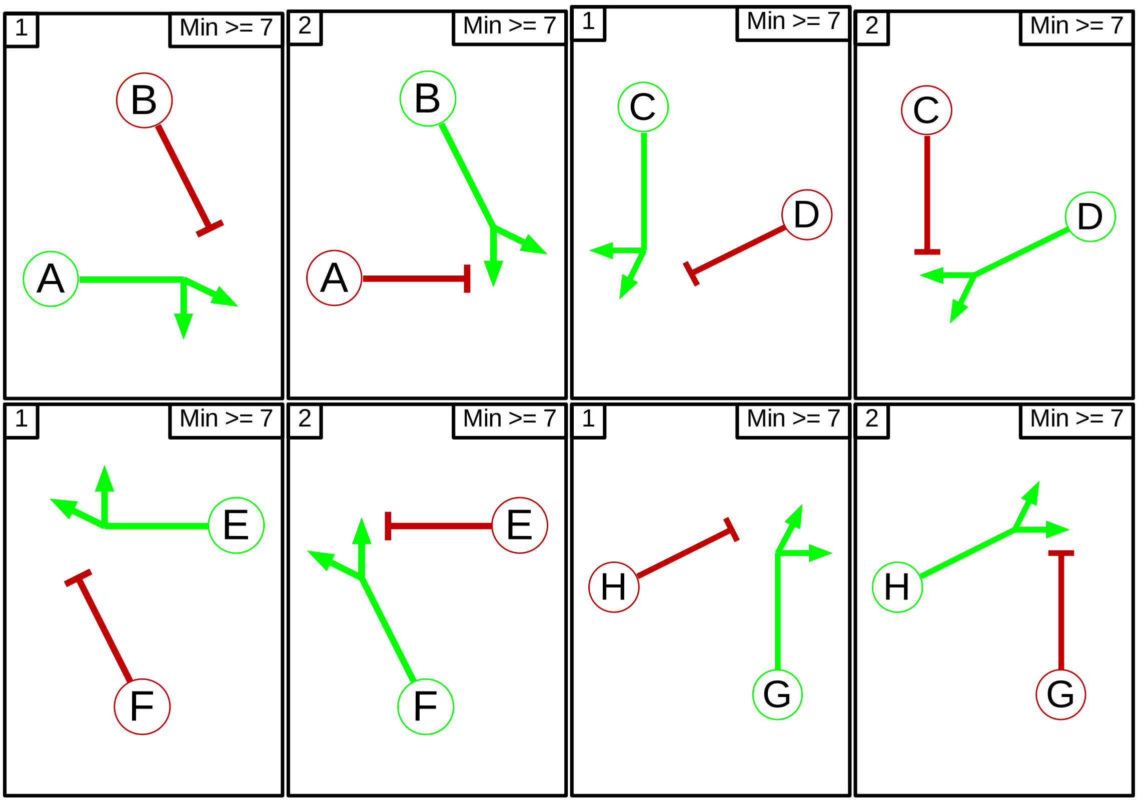


Figure 3.9 – Staging of the phase sequence of signalised roundabouts in the United Kingdom

The staging of the phase sequence can be seen from Figure 3.9 where the inner phases of A, C, E and G proceed before the entry lanes represented by B, D, F and H. The phase sequence follows a clockwise rotation around the roundabout with the inner phases proceeding before the entry lane phase to clear the roundabout before the addition of more vehicles within the circulating carriageway. This can be seen more diagrammatically in Appendix D.

The general inter-green time between all phases is set at two seconds to allow the clearance of the last vehicle entering under the current green phase from the approach of the following green phase. The phasing is optimised between both inner and outer phases that work concurrently with other grouped inner and outer phases. For example phase A can run concurrently with phases D, E and H and phase B can run concurrently with phases C, F and G. Attached in Appendix B is an example of a signal timings scheme for a 60 second cycle time.

Generally phase times within signalised roundabouts are kept short to allow quick rotation between phases to clear the inner circulating carriageway. Using this procedure allows the entering vehicles to be unaffected by stored queues within the circulating carriageway and allows them to effectively navigate to their desired destination.

3.2.3 Capacity

The installation of traffic signals has numerous effects on the capacity of a roundabout both in a saturated and un-saturated flow period. In saturated flows it eliminates the need for vehicles to find an acceptable gap to enter the roundabout and can control queuing caused from the demand of a singular heavy leg.

However it alters the traffic flow characteristics of the intersection to resemble a typical signalised intersection. This makes the intersection insufficient when there is a low traffic demand as it takes away the free flowing characteristics of an un-signalised roundabout forcing vehicles to stop in accordance with the phasing.

In comparison to un-signalised roundabouts the difference in capacity of a signalised roundabout specifically relies on headway during saturated flows. This is due to the signalisation eliminating the drivers need for gap acceptance, which heavily reduces the impact on driver behaviour towards capacity.

The entry capacity for a signalised roundabout treatment can be effectively worked out by:

$$Q = su \tag{3.5}$$

Where,

Q = capacity (veh/hr)

s = saturation flow rate (queue discharge) (veh/hr)

u = proportion of time vehicles can depart from the queue

In order to get the saturation flow rate for vehicles entering into the intersection the following equation is used:

$$s = 3600/h_s \tag{3.6}$$

Where,

h_s = queue discharge headway (seconds)

To find the proportion of time the vehicles are able to discharge into the intersection the following equation is used:

$$u = g/c \tag{3.7}$$

Where,

g = effective green time (seconds)

c = cycle time (seconds)

The capacity of a signalised roundabout is still affected by the roundabout geometry much the same as the impact it has on un-signalised roundabouts.

There are three key features between signalised roundabouts and conventional signal controlled intersections that impact on the capacity of the intersection. These are:

- The geometric elements of the intersections.
- The ability to store vehicles within the circulating carriageway of a roundabout.
- The use of the geometric layout of a roundabout to effectively use phasing to reduce periods of no vehicle movement between phases.

These features make comparing capacities of signalised roundabouts to signal controlled intersections unreliable and should not be used as a basis to judge the capacity of a signalised roundabout on.

Although there is extensive research done into the capacities of signalised intersections and how they compare to un-signalised roundabouts, there is little research done into the capacities of signalised roundabouts due to the relatively new implementation of them.

A recent study (Bernetti, Dall'Acqua & Longo 2003) based on the three lane circulating roundabout at Piazza Maggi (Milan) shown in Figure 3.10, compared the mean delays of the roundabout for un-signalised and signalised conditions based on three analytical approaches.

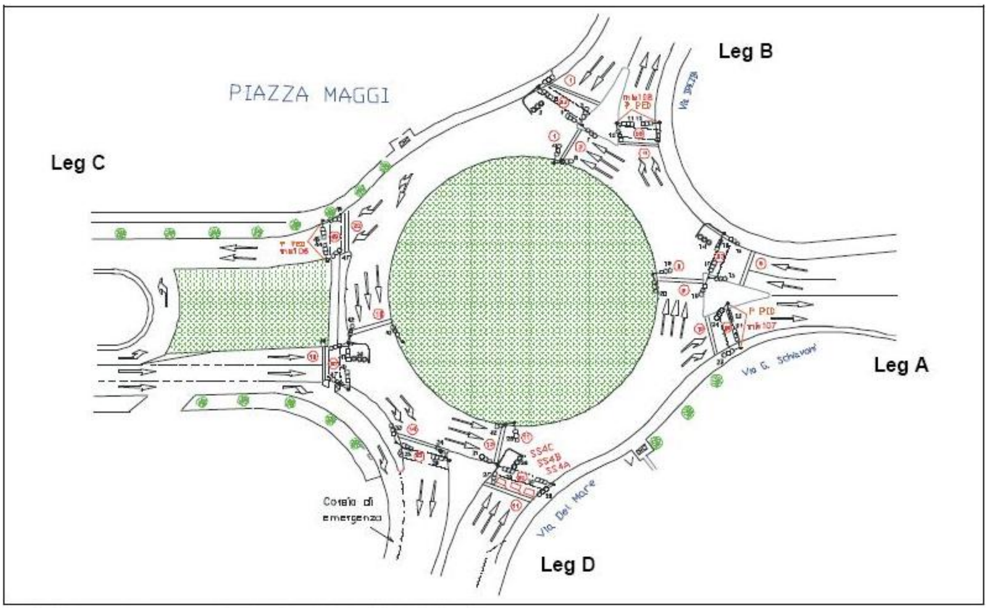


Figure 3.10 – Piazza Maggi Layout (Bernetti, Dall'Acqua & Longo 2003, Figure 1)

The three approaches used were as follows:

Un-signalised approaches

- The Austroads (1993) Australian method used in *Part 6 Guide to Traffic Engineering Practice.*
- The French approach proposed by SETRA in *Capacité des carrefours giratoires interurbains (1987)*

Signalised approach

- The mesoscopic model developed from proceedings of the European Transport Conference *A Mesoscopic model for evaluating Performance of signalised intersections (2002).*

Currently the intersection is a signalised four-leg roundabout that has approximately 7000 passenger car unit per hour pass through the intersection in peak hour flows. The average entry and circulatory widths are 13m and the inscribed circle diameter is 100m. Figure 3.11 shows the comparison of the mean delays for each approach relating to a percentage of the 7000 peak hour flow.

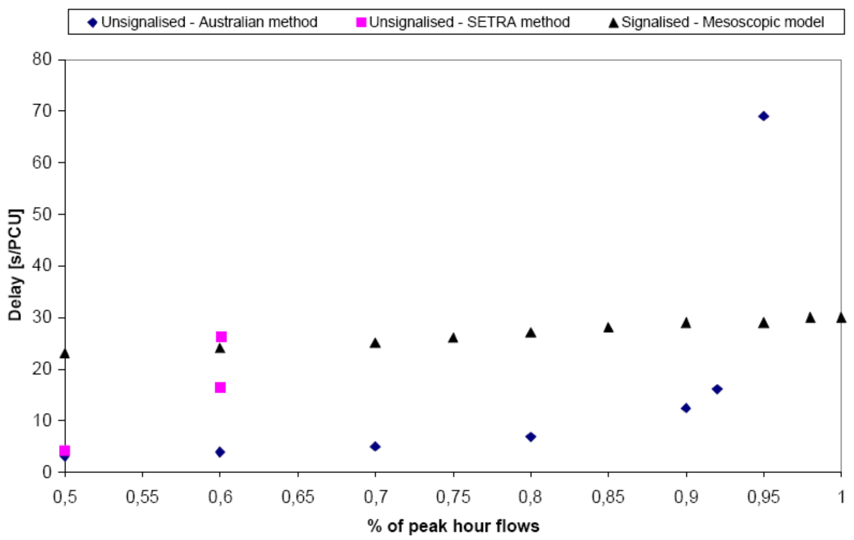


Figure 3.11 – Results comparison in terms of mean delays (Bernetti, Dall'Acqua & Longo 2003, Figure 6)

This figure immediately shows that when the percentage of traffic approaches peak hour flows, the signalised control of the intersection keeps mean delays consistently around 30 seconds. If the roundabout were to be un-signalised the mean delay would rapidly increase on approach to peak hour flows, increasing from 5 seconds at 80% of peak hour flow to 70 seconds at 95% of peak hour flow.

There are similar traffic flow characteristics of signal controlled intersections that relate to signalised roundabouts such as stop flow conditions, headways and pedestrian flows which will be used in analysing the capacity of signalised roundabouts. These characteristics will be discussed in further detail in the next section.

3.3 Traffic flow characteristics

As this report analyses the capacity of both signalised and un-signalised roundabouts, this section will detail the parameters and characteristic used to determine the traffic flow of a roundabout intersection.

There are several key characteristics of traffic flow that influence the capacity of roundabouts such as gap acceptance, headway distribution, roundabout geometry, traffic fleet and lane widths. These characteristics need to be analysed to suit the geographical behaviours of the designed roundabout due to the varying nature of these characteristics across the world.

3.3.1 Gap Acceptance

Gap acceptance is critical in dealing with capacities for un-signalised roundabouts, as a vehicle has to assess when it is safe to enter into the circulating carriageway. The driver will make a decision as to what they think is a safe gap which ideally will not impact the circulating traffic. However during high circulating flow periods drivers tend to forcefully enter causing circulating traffic to give-way to entering vehicles. This is known as a forced gap and reversed priority.

Gap

Austroads (2008) states that, a gap is the magnitude of the time interval considered acceptable to undertake a manoeuvre into a conflicting traffic stream and depends on the road geometry site, the characteristics of the traffic and the nature of the manoeuvre itself. The definition of a gap presented to an entering vehicle is shown in Figure 3.12.

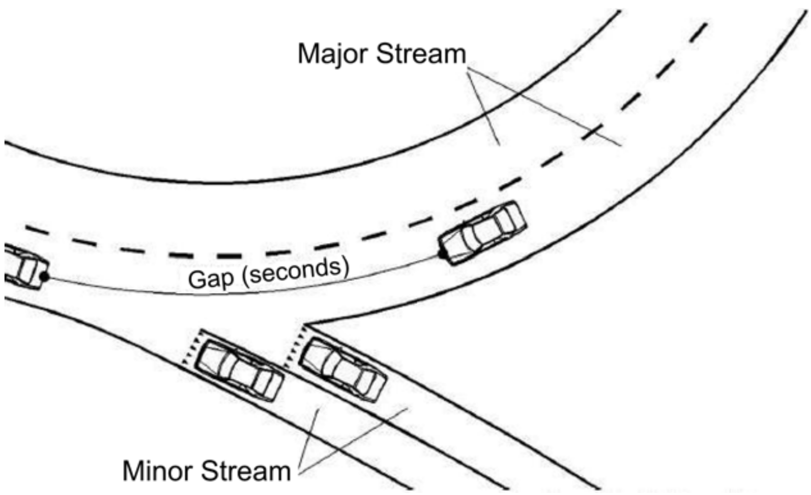


Figure 3.12 – Definition of a gap (Irvena 2010, Figure 3.3)

Lag

The gap accepted by the driver can be used by more than one vehicle. The following vehicles that enter within the gap that the first vehicle accepts is said to be using the lag. Lag is the distance in time between the entering vehicle and the successive vehicle in the major stream and is shown in Figure 3.13 (Drew 1968, p 177).

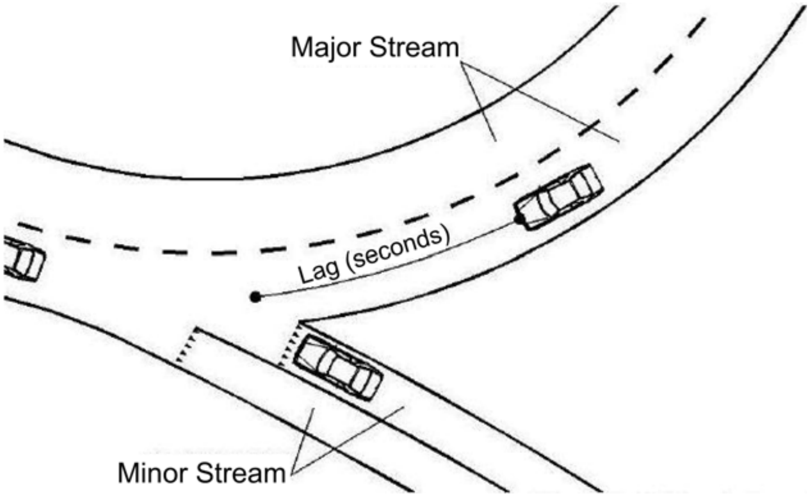


Figure 3.13 – Definition of lag (Irvena, 2010, Figure 3.4)

Critical Gap

During vehicle entry into the circulating carriageway there is a critical gap which all drivers will accept. The gap is known as the critical gap which is the minimum accepted gap by all drivers at all times. It is generally based on the observed gap acceptances and rejections at existing roundabouts.

For example, 'Raff and Hart (1950) proposed a method in which a diagram similar to Figure 3.14 is plotted from field observations and the critical gap is taken to be the gap 'T' corresponding to the intersection of the acceptance and rejection curves' (Austroads 2008).

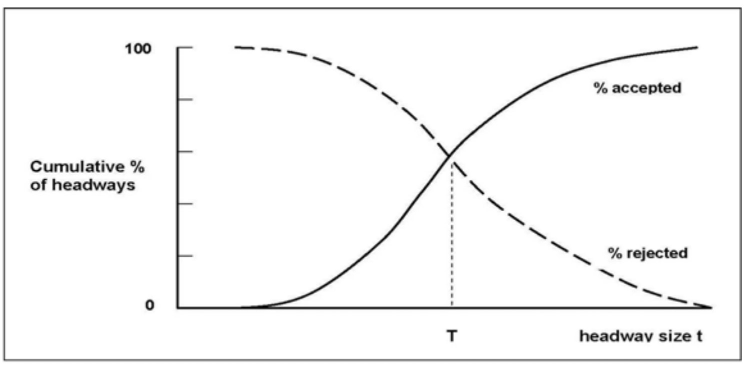


Figure 3.14 – Typical Gap Acceptance behaviour (Austroads 2008, Figure 5.1)

'Akçelik (2011) documented a critical gap range of 2.2 to 8.0 seconds and a follow-up headway of 1.2 to 4.0 seconds' (Seiberlich 2001). These figures were based on dominant and subdominant lane utilisation discussed in section 3.4.1.1 of this report.

Further research from Akçelik (2011) shown in Figure 3.15 determines that when circulating flow approaches a higher capacity the critical gap of the dominant lane will accept a smaller gap. This relates to driver behaviour, as drivers experiencing longer delays will become more aggressive in accepting gaps and may cause circulating traffic to give-way forcing reversed priority.

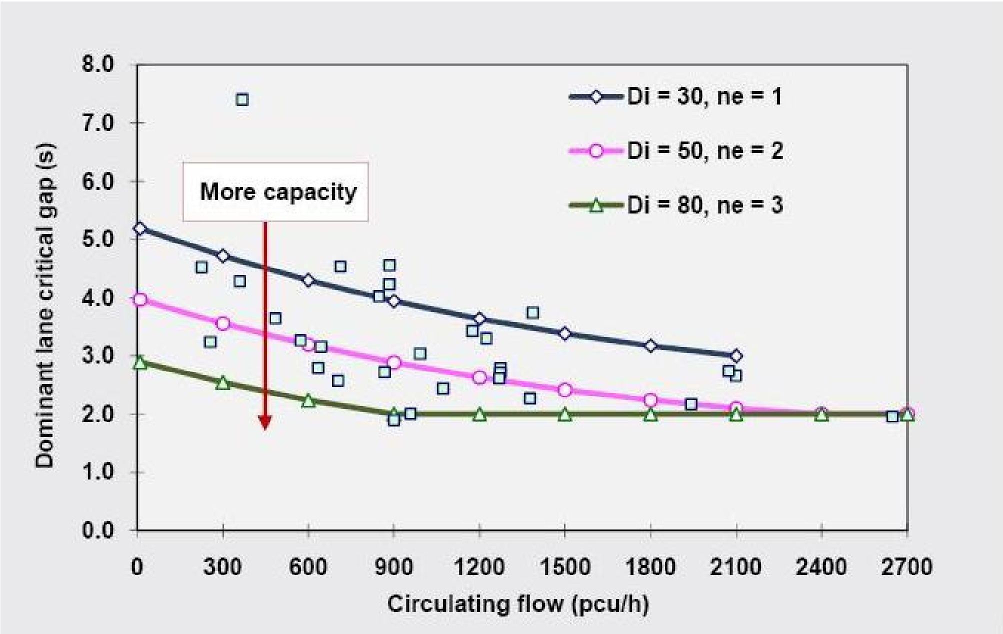


Figure 3.15 – Critical gap with increased circulating flow (Akçelik, 2011)

3.3.2 Headways

Headway Distribution

Headway is the time between two following vehicles and is measured from the front of the first vehicle to the front of the following vehicle. The headway distribution is used to describe the traffic flow in the opposing traffic stream. Headway distribution has a great impact on the capacity of un-signalised roundabouts. The definition of a headway is shown in Figure 3.16

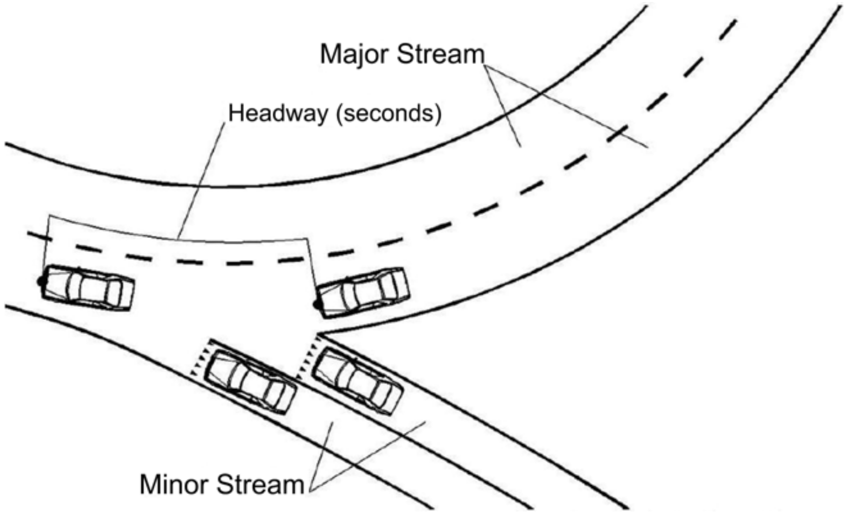


Figure 3.16 – Definition of headway (Irvena 2010, Figure 3.6)

Follow-up Headway

The time that occurs between the first entering vehicle and successive following vehicles is called the follow-up headway. This is the distance measured from the same reference point on each successive car and can only be measured when there is a queue situation. This is shown in Figure 3.17.

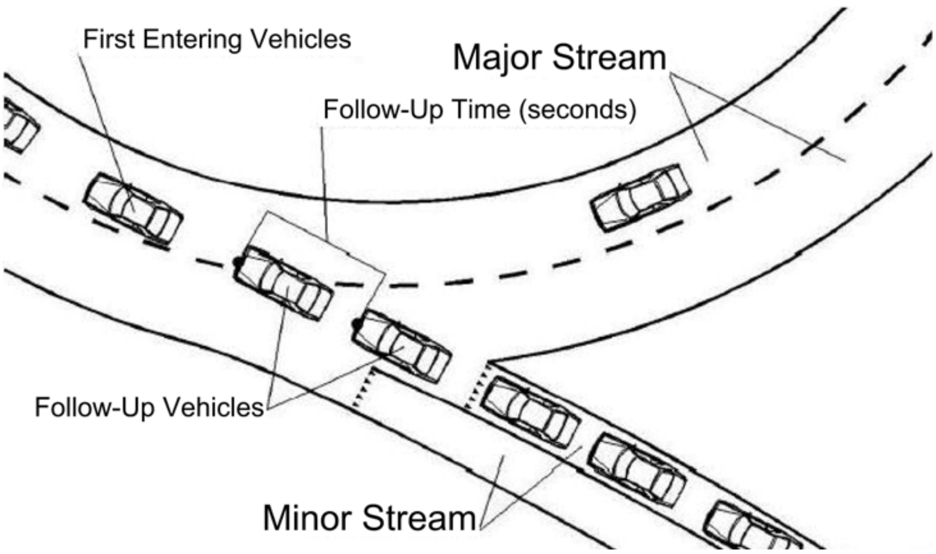


Figure 3.17 – Definition follow-up headway (Irvena 2010, Figure 3.5)

Under signalised conditions the follow-up headway is a major parameter when calculating entry capacity of an intersection. Due to the red phase of signalisation causing a queue situation the observed follow-up headway once the signal turns green for vehicles is shown in Figure 3.18.

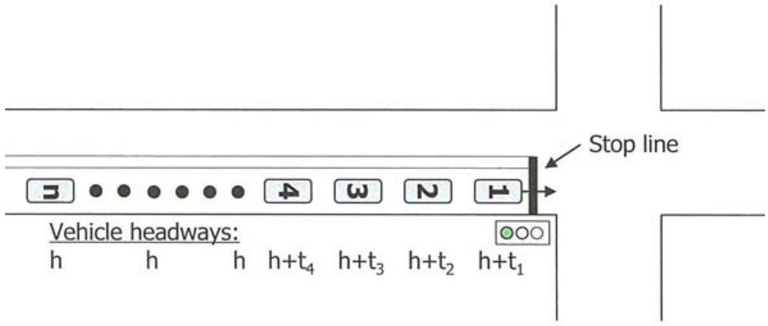


Figure 3.18 – Signalised intersection acceleration headways (HCM 2010, Exhibit 4-6)

The observed headways are varied due to the acceleration of entry into the intersection. The HCM (2010) shows that after the fourth vehicle follow-up headways become consistent.

The HCM (2010) recommends using the fifth vehicle following the beginning of a green as the starting point for saturation flow measurements as shown in Figure 3.19.

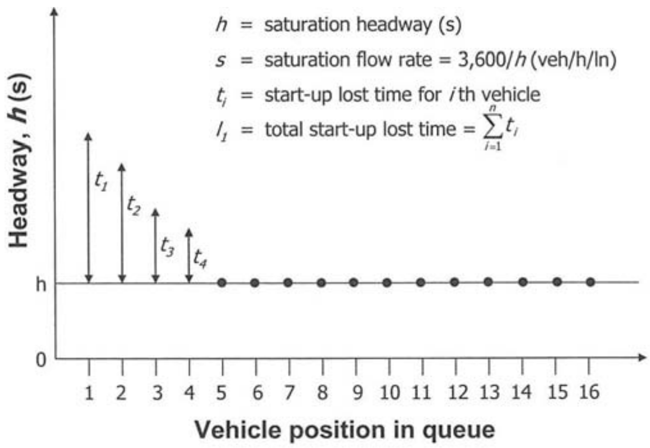


Figure 3.19 – Concept of saturation flow rate and lost time (HCM 2010, Exhibit 4-7)

The value h represents the *saturation headway* which is the average constant headway measured after the fourth entering vehicle after being stopped by a traffic signal. The *saturation flow rate* is computed by:

$$s = 3600 / h \tag{3.8}$$

Where:

s = saturation flow rate (veh/hr)

h = saturation headway (s)

The saturation flow rate stated in equation 3.3 is based on a green signal displayed for a full hour with the flow of vehicles continuously approaching at the same rate and no large headways in between vehicles.

Austroads states that *"In many cases, a key decision for the traffic analyst is the selection of the type of headway distribution that is either:*

- *Most likely to correspond with the traffic situation under consideration.*
- *Likely to best match a set of headways that has been observed in field measurements."*

For the second case this report will base its follow-up headways on observed headways taken from signalised intersection field studies.

3.3.3 Traffic Composition

Traffic composition needs to be considered when determining capacities for both un-signalised and signalised roundabouts. The increase of heavy vehicles will reduce the capacities of the intersection due to their slow follow-up headways and increased size.

Akçelik (1997) recommended that passenger car equivalents (pce) per hour be used instead of vehicles per hour when the proportion of heavy vehicles is greater than 5%. Passenger car equivalents allow heavy vehicles to resemble a standard passenger vehicle to better represent the capacity of an intersection.

Typically the passenger car equivalent of a heavy vehicle is taken as 2.0. The Transport Research Board HCM suggests that the conversion factors for passenger car equivalents shown in Table 3.3 be used:

Table 3.3 – Conversion factors for passenger car equivalents (pce) (HCM 2010, Exhibit 4-5)

Vehicle Type	Passenger Car Equivalent (pce)
Car	1.0
Heavy Vehicle	2.0
Bicycle	0.5

3.3.4 Saturation Flow

Saturation flow measures the volume to capacity ratio of a lane. It is based on the ratio of the volume of vehicles travelling through the lane to the capacity that the lane is able to provide. When the degree of saturation reaches 100% the lane is unable to allow any extra demand in vehicles, if more traffic demand is required the lane will be subject to increasing queue lengths.

Typical values used in TRL UK methods, for lane saturation flows for signalised roundabouts are 1900 pcu/hr. For turning movements under full signalised conditions a typical value of 1800 pcu/hr is used.

3.3.5 Roundabout Geometry

Inscribed diameter Un-signalised roundabouts

Akçelik (2011) states that with increased inscribed diameter capacity increases for un-signalised roundabouts and then decreases for very large diameters. Shown in Figure 3.20 is the capacity and critical degree of saturation based on a percentage scale of a 40m un-signalised diameter roundabout.

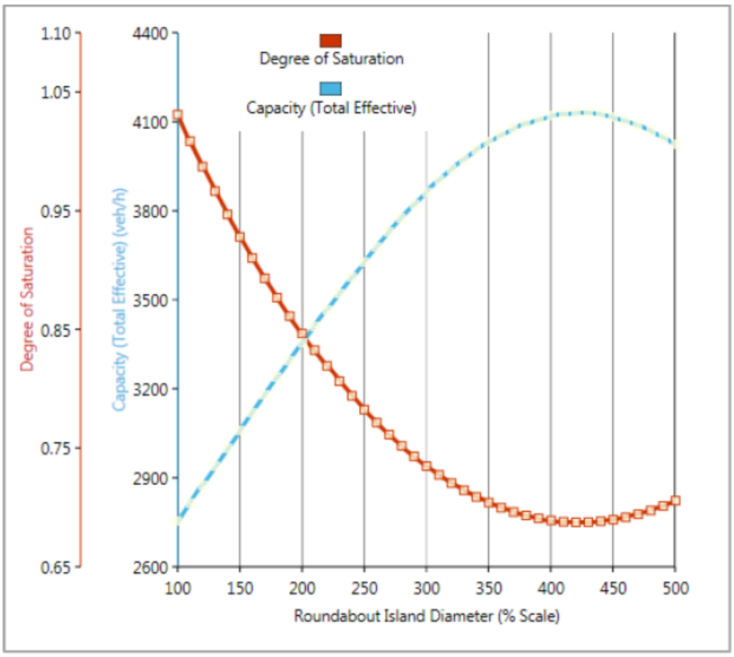


Figure 3.20 – Effective intersection capacity and critical degree of saturation as a function of inscribed diameter estimated by Australian gap acceptance theory (Akçelik 2011, Figure 5)

This shows that once the roundabout diameter approaches 4 times that of a 40m roundabout (160m) the capacity actually decreases. As this report will be based on inscribed diameters of 40m to 60m which are the most common two lane roundabout sizes found within Australia, it assumes that with the increased inscribed circle diameter the capacity of an un-signalised roundabout will increase.

Inscribed diameter Signalised roundabouts

Although there is not as much research into the effect of the inscribed diameter on signalised roundabouts compared to un-signalised there are three key areas that the inscribed diameter will impact on the capacity.

- It can cause longer clearance times between phases due to longer travel path of vehicle around the central island.
- The ability to use the circulating carriageway as storage area for vehicles in between phases
- The ability to use longer clearance times along with the geometry of the roundabout to phase signals effectively so that vehicles are still travelling within phase changes.

These points will be assessed within this report and will examine what impact the increased diameter has on the capacity of signalised roundabouts.

Entry Lane width and Number of entry lanes

The Federal Highway Administration (2000), states that the number of entry lanes is a major factor for capacity. The increased number of entry lanes effectively doubles the capacity of the roundabout.

This report will be based on providing two entry lanes for all four approaches into the circulating carriageway of the roundabout. The entry lane widths will be 4m wide providing an entry width of 8m in total. These entry lane widths are based on Roads and Maritime Services (RMS) NSW and Austroads guidelines found in Austroads *(2011).*

The entry lane width can be critical to the saturation flow through the lane on entering the roundabout. If the lane widths are too narrow vehicles will feel squeezed on entering thus reducing their entry speed and reducing the capacity of that lane.

Circulating lanes

Circulating lanes should correspond to the number of entry lanes provided into the roundabout. This report will examine a two lane circulating carriageway with a circulating road width of 11m based on RMS and Austroads (2011).

Entry angle

The entry angle is governed by the bearing of the entry arm and the radius of the entry curve into the roundabout. It is desirable to provide a sight angle between 70° to 90° to provide efficient sight line for approaching traffic.

Entry angles for this research will be based on 90 degree intersection of entry arms with 50m radius entry curves.

Grades

'It is generally not desirable to locate roundabouts in locations where grades through the intersection are greater than four percent' (FHWA, 2000). Generally large two lane roundabouts are constructed on relatively flat grades. Due to this case grading will not be taken into account when calculating capacities of the roundabout.

3.3.6 Lane Widths

Standard lane widths used in Australia at roundabout intersections are 3.5m lanes that increase to 4m on entry into the circulating carriageway. The impact lane widths have on the capacity of roundabouts is said to be negligible.

The 3.5m lane width has been tested to produce the most effective saturation of flow per lane at a safe clearance width for vehicles and still is cost effective to build. The increase to 4m upon approach to the roundabout intersection is to provide extra width for turning vehicles within the entry radius and increase driver comfort with extra width for entering the intersection.

The report will examine the effect varying lane widths have on the impact to the capacity of a roundabout.

3.4 Analytical Methods & Capacity Measures

3.4.1 Analysis Methods for Un-Signalised Roundabouts

Across the world there has been the development of two dominant types of methods to determine the capacities of un-signalised roundabouts. These include the gap acceptance theory which is typically used in Australia & USA and empirical regression model which is typically used in UK, France & Switzerland. Shown in Table 3.4 are the analytical methods used throughout the world.

Table 3.4 – Analytical methods used across the world un-signalised roundabouts (Bernetti, Dall'Acqua & Longo 2003*, p 3)*

Analysis Method	Gap Acceptance Theory	Empirical Regression
Australia (Austroads)	Capacity & Delay	
France (SETRA)		Capacity & Delay
France (CETUR)		Capacity
Germany (Brilon)	Capacity	Capacity
Switzerland (VSS)		Capacity
Switzerland (Bovy)		Capacity
United Kingdom (Kimber)		Capacity & Delay
USA (HCM)	Capacity & Delay	

Findings from the National Cooperative Highway Research Program (NCHRP, 2007) on US roundabouts found that the capacity of an un-signalised roundabout cannot be based on geometry alone. In fact it found that driver behaviour is the largest variable affecting roundabout performance although 'geometry in the aggregate sense (number of lanes) has a clear effect on the capacity of a roundabout entry' (Akçelik 2009).

The empirical method calculates capacity based on geometry alone as it tried to establish a worldwide analysis method that eliminates the variability of driver behaviour. The gap acceptance theory identifies parameters for critical gap, lane utilisation, passenger car equivalents (pce) of heavy vehicles and follow-up headways, along with the geometry of a roundabout to better represent the true behaviour of an un-signalised roundabout intersection.

The gap acceptance theory has been extensively developed by Akcelik who is the founder of SIDRA Solutions. This theory has been adopted in Australia as parameters used in this theory have been based on extensive field testing on Australian roads. This section will give a background on the two dominant theories developed for determining capacities of un-signalised roundabouts.

3.4.1.1 Analytical (Gap Acceptance)

The simplified gap acceptance theory is based on gap acceptance and headway measures stated in section 3.1.1 and 3.1.2 respectively. It determines the effective gaps produced from the circulating flow that allow entering vehicles into the roundabout. With increased circulating flow, gap acceptance decreases for entering vehicles causing increased delay times and queue lengths.

Akçelik (2007) claims that the approach of the SIDRA software gap acceptance approach goes beyond the simplified gap acceptance theory approach. ‘The current Australian analysis is largely based on field data collected and analysis procedures developed at ARRB’ (Troutbeck 1989).

The base parameters that define the capacity of the roundabout in this theory include:

- Inscribed circle diameter
- Average entry lane width
- Number of circulating lanes
- Number of entry lanes
- Entry capacity
- Ratio of entry flow to circulating flow

This theory also identifies the importance of dominant and subdominant entry lanes based on their flows. This is due to the fact that dominant and subdominant lanes can have different critical gap and follow up times. This identification differs from the old Australian NAASRA 1986 model where fixed gap-acceptance parameters were used where follow-up headways = 2.0s and critical gap = 4.0s.

The importance of the dominant and subdominant approach plays an important role when dealing with multi lane roundabouts. This is due to the fact that right lane entering vehicles (left lane for US) have to find a gap across two lanes of circulating traffic where the left lane can enter only giving away to one lane.

Also taken into account in Akçelik's gap acceptance theory is the use of passenger car equivalents (pce) to account for heavy vehicles. Akçelik (1997) recommended that pce per hour be used in place of vehicles per hour when the proportion of heavy vehicles surpassed 5%.

3.4.1.2 Empirical Regression (Geometric)

The empirical regression model was first developed in the UK by Kimber (1980). 'In Kimber's initial laboratory report (1980) he states that the dependence on entry capacity on circulating flow depends on the roundabout geometry' (Seiberlich 2001). The five geometric elements Kimber defines as having an impact on the capacity of a roundabout are:

- Entry width
- Entry flare
- Inscribed circle diameter
- Angle of entry
- Radius of entry

Kimber (1980) makes two interesting remarks on the use of the gap acceptance theory. Kimber states that the gap acceptance theory fails to represent the drivers behaviour in giving-way on approach to the roundabout. He also comments that because of the variance in driver behaviour it is not practical to apply this theory across the world.

These statements Kimber assumes are based on simple gap acceptance theories that were developed in the 1980's. Today Akçelik (2007) claims that the gap acceptance theory goes beyond a simple approach and includes parameters based on extensive field research and testing.

The empirical method does not allow for unequal lane utilisation as it is not based on singular lane approach use. This limits the empirical method as it does not cater for uneven approach demands which can be a critical parameter in dealing with multi lane roundabouts.

3.4.2 Analysis Methods for Signalised Roundabouts

Analysis methods for signalised roundabouts will be based on traffic theory approaches towards typical signal controlled sites. The main difference signalised roundabouts have to the typical signal controlled site is:

- Roundabout geometry is larger, therefore requiring a longer travel time to navigate through the intersection.
- The ability to store vehicles within the intersection.
- The ability to use longer clearance times along with the geometry of the roundabout to phase signals effectively so that vehicles are still travelling within phase changes.

The analysis method will be based on computer simulation using the computer software LinSig and Excel. The parameters used within Linsig are dealt within Section 3 of this report.

3.4.3 Control Delay

Delay is an important measure when analysing interrupted flow system elements. There are several types of delay, but *control delay* – the delay brought about by the presence of a traffic control device – is the principal service measure in the HCM 2010 for evaluating the level of service (LOS) at signalised and un-signalised intersections (HCM 2010, p 4-15).

Control delay incorporates the delay of a vehicle slowing down in advance of the intersection, the time spent stopped on the approach and the time spent navigating within the intersection to their desired exit upon reaching the vehicles desired speed. If the travellers' desired speed is reached before the exit of the roundabout intersection, the traveller will still experience geometric delay based on the travel path of the roundabout itself.

Akçelik (2009) produces tables based on control delay relating to the level of service of the intersection. The control delay times relating to level of service criteria is shown below in Table 3.5.

Table 3.5 – Level of service definitions for vehicles based on delay (Source: Akçelik 2009, Table 4)

Level of Service	Control delay per vehicle in seconds (d)		
	Signals	Roundabouts	Stop and Give-Way / Yield Signs
A	d ≤ 10	d ≤ 10	d ≤ 10
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25
D	35 < d ≤ **55**	35 < d ≤ **50**	25 < d ≤ **35**
E	**55** < d ≤ 80	**50** < d ≤ 70	**35** < d ≤ 50
F	80 < d	70 < d	50 < d

This criteria will be used on assessing the capacity of signalised roundabouts along with discussion of level of service in section 3.4.4.

3.4.4 Level of Service (LOS)

Austroads (2008) quotes "Level of service is a qualitative measure describing operational conditions within a traffic stream, and their perception by motorists and/or passengers."

The level of service criteria simplifies the traffic flow parameters such as delay, speed, travel time, comfort, safety and freedom to manoeuvre into a simplified A to F scale, where A represents ideal conditions based on the traveller's perspective and F represents the worst conditions.

The six levels of service criteria are represented in the Highway Capacity Manual (2010) detail given in Table 3.6:

Table 3.6 – Descriptions of Level of service for interrupted flow

LOS A	Primarily free flow operations at average travel speeds, usually about 90% of the FFS (free flow speed) for the given street class. Vehicles are completely unimpeded in their ability to manoeuvre within the traffic stream. Control delay at signalised intersections is minimal.
LOS B	Reasonably unimpeded operations at average travel speeds, usually about 70% of the FFS for the street class. The ability to manoeuvre within the traffic stream is only slightly restricted and control delays at signalised intersections are not significant.
LOS C	Stable operations; however, ability to manoeuvre and change lanes in mid-block locations may be more restricted than at LOS B and longer queues, adverse signal coordination, or both may contribute to lower average travel speeds of about 50% of the FFS for the street class.
LOS D	A range in which small increases in flow may cause substantial increases in delay and decreases in travel speed. LOS D may be due to adverse signal progression, inappropriate signal timing, high volumes, or a combination of these factors. Average travel speeds are about 40% of FFS.
LOS E	Characterised by significant delays and average travel speeds of 33% of the FFS or less. Such operations are caused by a combination of adverse progression, high signal density, high volumes, extensive delays at critical intersections and inappropriate signal timing.
LOS F	Characterised by urban street flow at extremely low speeds, typically 25% to 33% of the FFS. Intersection congestion is likely at critical signalised locations, with high delays, high volumes and extensive queuing.

Level of service is based on a step function. HCM 2010 states *'An increase in average control delay of 12 s at a traffic signal, for example, may result in no change in LOS, a drop of one level, or even a drop of two levels, depending on the starting value of delay.'* This is represented in Figure 3.21.

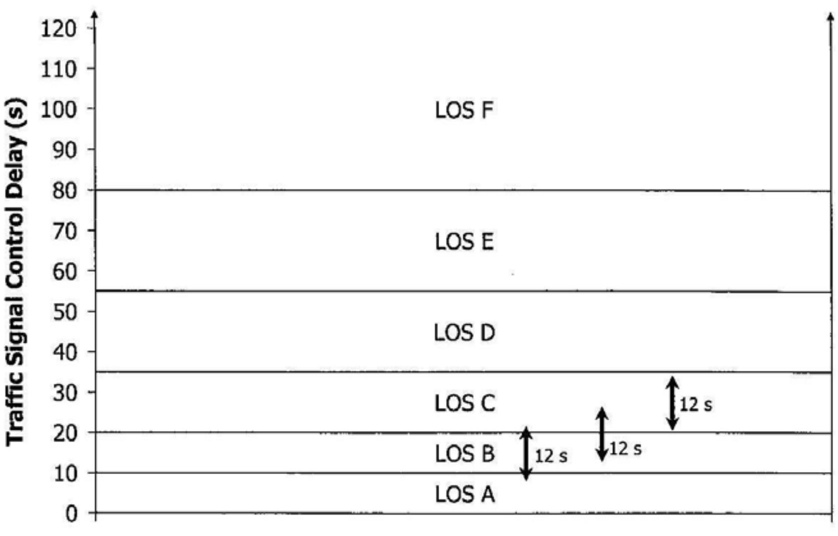


Figure 3.21 – Step function nature of Level of Service (HCM 2010, Exhibit 5-1)

This shows that a increase of delay of 12 seconds may not necessarily decrease the level of service criteria as it depends on the original average delay. Even though the driver will experience a decreased level of service through the intersection, this will not be reflected under the A to F level of service criteria. This should be noted when assessing the delay of an intersection based on level of service criteria.

Level of service can also relate to the degree of saturation. The degree of saturation is the demand at the roundabout entry to the capacity of the entry. This is measured as a volume to capacity ratio and can be used as well for the ratio of total entering volumes to the total capacity of the roundabout.

Akçelik (2009) produces the table shown in Table 3.7 which determines the level of service criteria to both the delay and degree of saturation.

Table 3.7 – Level of service definitions for vehicles based on both delay and degree of saturation (Source: Akçelik 2009, Table 5)

Level of Service	Control delay per vehicle in seconds (d)			Degree of saturation (v/c ratio) (x)
	Signals	Roundabouts	Stop and Give-Way / Yield Signs	
A	$d \le 10$	$d \le 10$	$d \le 10$	$0 < x \le 0.85$
B	$10 < d \le 20$	$10 < d \le 20$	$10 < d \le 15$	$0 < x \le 0.85$
C	$20 < d \le 35$	$20 < d \le 35$	$15 < d \le 25$	$0 < x \le 0.85$
D	$35 < d \le 55$	$30 < d \le 50$	$25 < d \le 35$	$0 < x \le 0.85$
	$0 < d \le 55$	$0 < d \le 50$	$0 < d \le 35$	$0.85 < x \le 0.95$
E	$55 < d \le 80$	$50 < d \le 70$	$35 < d \le 50$	$0 < x \le 0.95$
	$0 < d \le 80$	$0 < d \le 70$	$0 < d \le 50$	$0.95 < x \le 1.00$
F	$80 < d$	$70 < d$	$50 < d$	$1.00 < x$

Table 3.7 will be used as the basis in determining the limits of capacity for the examined signalised roundabouts analysed using the LinSig software.

3.5 Computer Software Modelling

The computer software modelling will take into account key design features stated in the previous section and apply them in the development of the roundabout model to analyse the capacity of the roundabout when applied with various traffic volumes. The computer software modelling package that will be used for this project is LinSig.

3.5.1 LinSig

'LinSig is a computer software package for the assessment and design of traffic signal junctions either individually or as a network comprised of a number of junctions' (JCT, 2011). The software was established in the United Kingdom and has been developed through numerous versions since 1985.

'It differs from other simpler computer software modelling packages such as SIDRA, as it can be used for multiple traffic signal junctions, complex compound junctions such as signalised roundabouts and road networks which may include traffic signal pedestrian crossings and priority junctions as well as traffic signal junctions' (JCT, 2011).

Linsig's input data specifies traffic flows as sets of origin to destination matrices that gives entry to exit movement. These movements form the basis of the lane flow diagrams LinSig is able to develop.

3.5.2 Level of Service (LOS)

Linsig allows the user to optimise the traffic flow of the intersection across two different approaches. The two approaches are:

- Delay based assignment
- Entry lane balancing

Delay based assignment will assign traffic to routes so that the journey time between routes with the same origin and destination zones are as equal as possible.

Entry lane balancing will allocate traffic to routes in order to balance the entry arm lanes as equally as possible.

Linsig also uses a maximum base degree saturation of 90% when optimising cycle times. This makes the program alter cycle times to keep the degree of saturation of each lane throughout the intersection to a maximum 90% degree of saturation.

The 90% value is used to leave a 10% margin of error when calculating the mean maximum queue length over the hour period. This is used to eliminate peak values over the hour period that will exceed the 90% value and allows the lane to stay under the 100% degree of saturation. If the value was able to exceed the 100% degree of saturation, the intersection would be subjected to an increasing queue length causing it to fail in the demand for capacity.

4. DESIGN AND METHODOLOGY

4.1 Aims and Objectives

The projects aim is to investigate the capacity of a two lane signalised roundabout based on the phasing structure stated in section 3.2.2 and section 4.4.

The basic programme of the project is as follows:

- A complete review of local and overseas researches on traffic flow characteristics at un-signalised and signalised roundabouts.
- Develop traffic capacity models with various radii using Excel and LinSig, which is a computer software programme that assesses the design of signalised roundabouts and intersections.
- Apply uniform traffic flows to each leg of the intersection and assess the impact of traffic flows on queue lengths and level of service.
- Establish relationships between design parameters (radius, queue discharge headways, phase cycle times) and the capacity of a signalised roundabout.
- Compare the traffic flow capacity of signalised roundabouts to conventional un-signalised roundabout designs.

4.2 Methodology

The basis of determining the capacity of a roundabout can be seen from the HCM (2010) shown in Figure 4.1.

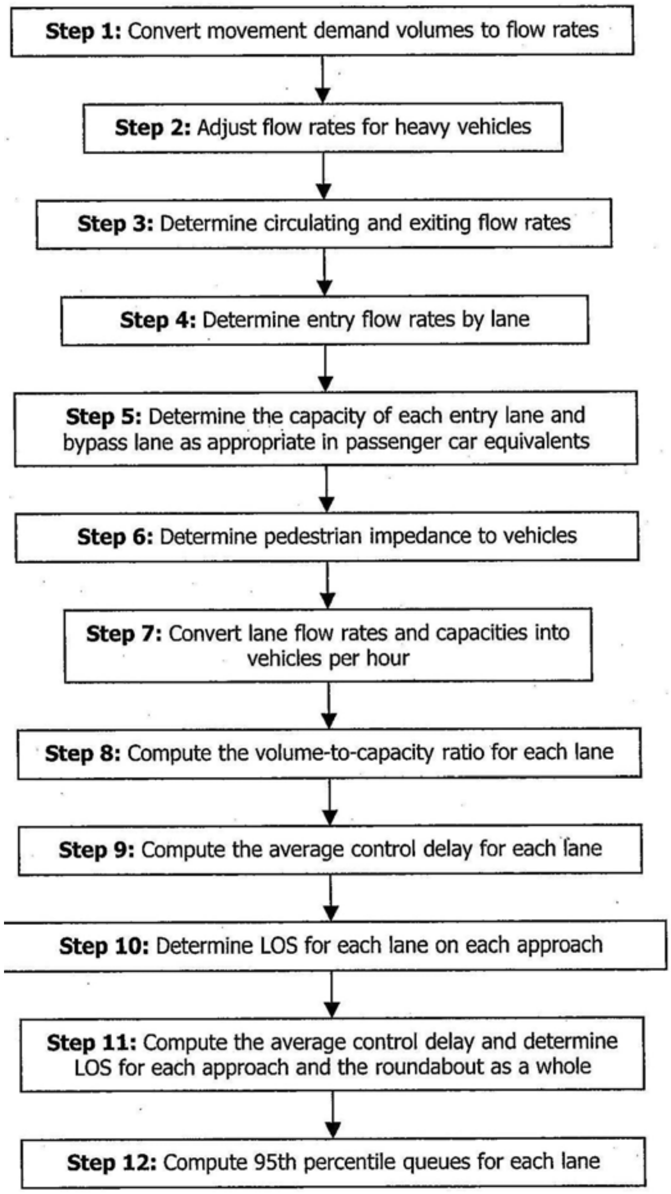


Figure 4.1 – Roundabout Analysis Methodology (HCM 2010, Exhibit 21-9)

Figure 4.2 represents the methodology determined from the HCM (2010) of calculating automobile performance for a signalised intersection.

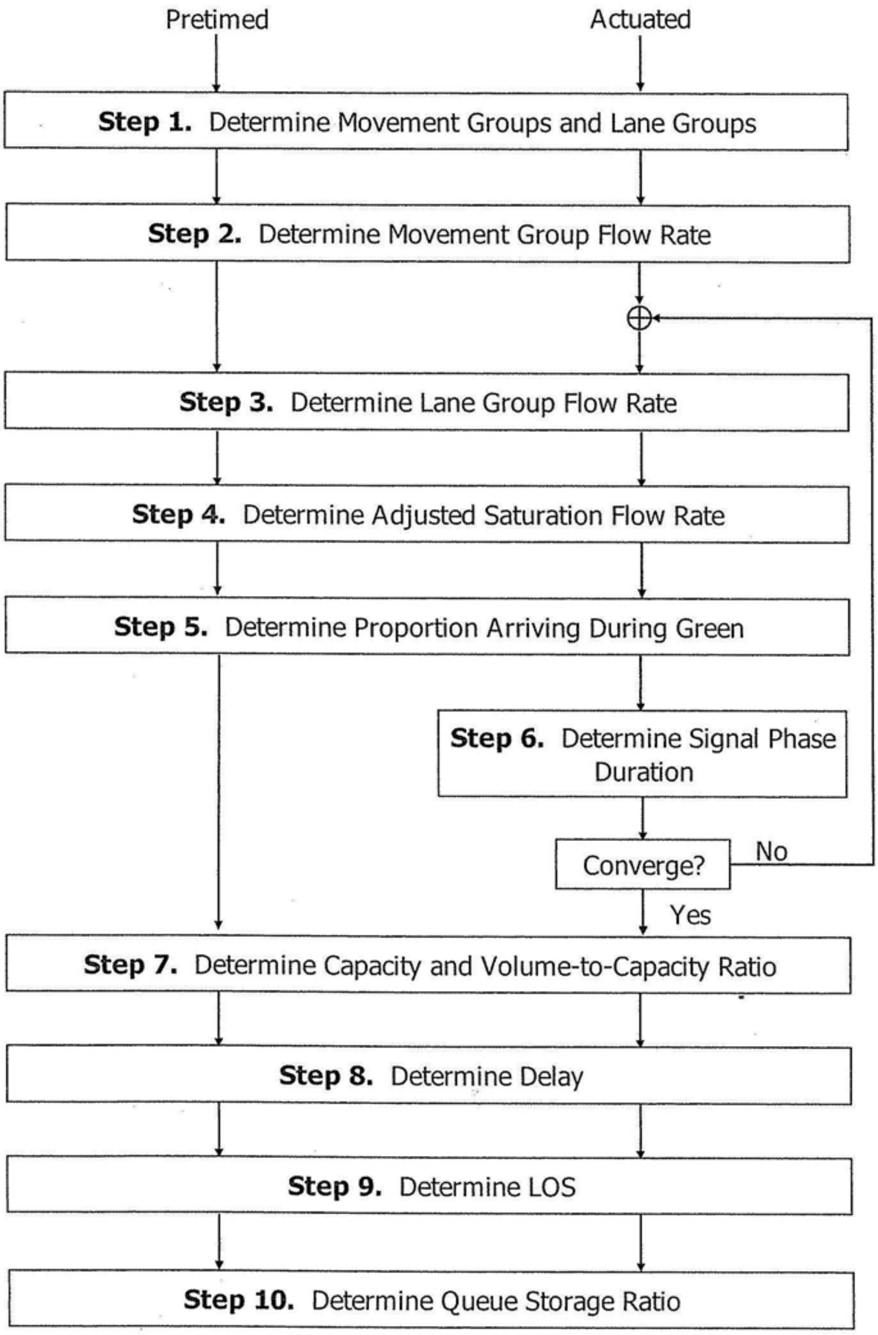


Figure 4.2 – Signalised Intersection Analysis Methodology (HCM 2010, Exhibit 18-11)

The methodology described in Figure 4.2 has to be combined with Figure 4.1 to determine the required inputs for the computer software packages LinSig and Excel. The required methodology for this project is to:

- Research common inscribed diameter sizes used for two lane roundabouts across Australia.
- Base input data on the research provided in section three of this report and also on field research conducted. Data required to analyse the capacities of signalised roundabouts can be found in Table 4.1.
- Develop LinSig and Excel models based on variable inscribed diameters designed using Austroads (2011) standards for roundabout layouts.
- Input data based on research and field tests into the Linsig and Excel models to allow the computer model to calculate capacities.
- Apply uniform demand flow rates for vehicles across all approach legs.
- Analyse LOS and degree of saturation of lanes to determine when the intersection reaches capacity.
- Compare the flow rates with the capacity of an un-signalised case.
- Compare all documented results within LinSig and Excel from uniform demand flows on both signalised/un-signalised cases.
- Discuss and report results.
- Conclude discussions based on results.

4.3 Data inputs for Linsig Models

Table 4.1 represents the data inputs required to be input into the LinSig models to determine the capacity, delay and LOS criteria.

Table 4.1 – Input data for LinSig models

Data Category	Input Data Element	Input Basis
Traffic Characteristics	Demand Flow Rate	Variable flow rates applied
	Origin to destination matrix	Variable matrices applied
	Percent Heavy Vehicles	All flows will be in pcu
	Pedestrian flow rate	Variable flow rates applied
	Bicycle flow rate	Variable flow rates applied
	Follow-up headway	Based on field research
Geometric Design	Number of lanes	2
	Average lane width	3.5m
	Number of receiving lanes	2
	Lane Length	greater than 500m
	Geometric Delay	Based on inscribed diameter inserted by cruise times
	Approach grade	0%
Signal Control	Type of signal control	Pre-timed
	Phase sequence	Refer to Figure 4.3 Section 4.4
	Green time	Variable length - same time for each leg
	Yellow change time	3 seconds
	Red clearance	Variable (refer to section 4.4.1)
	Pedestrian/cyclist walk time	Variable based on distance
	Pedestrian/cyclist clear time	6 seconds
Other	Analysis period duration	60, 75, 90 and 105 second cycle time
	Speed Limit	60km/h
	Area type	Variable depending on inscribed diameter

4.4 Phase Sequence

The phase sequence used to analyse the signalised roundabout models is different to the general phase sequence used in the United Kingdom and is shown in Figure 4.3.

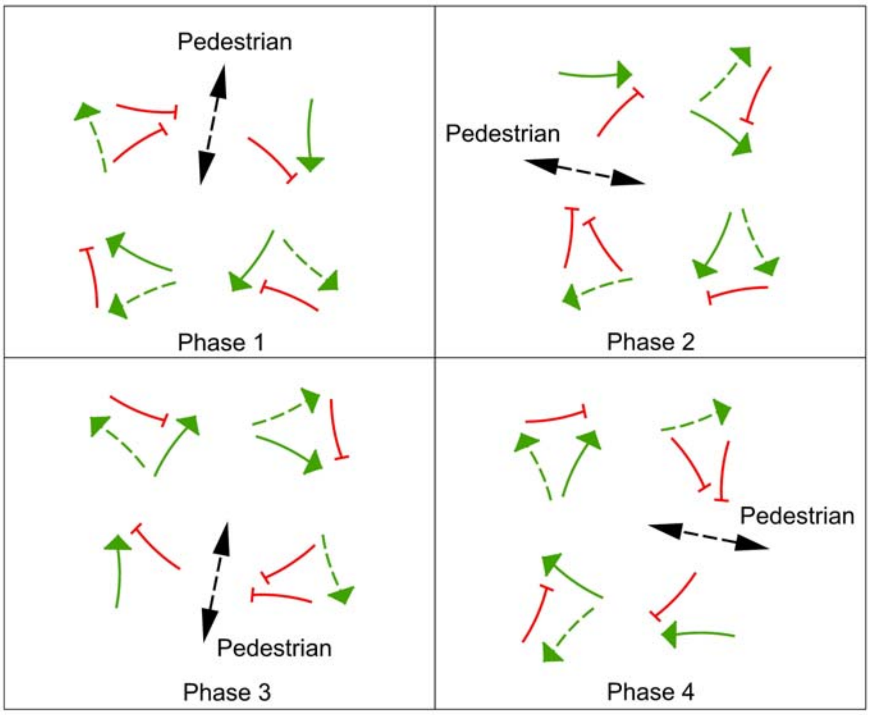


Figure 4.3 – Phase sequence used to examine capacity of signalised roundabout

This phase sequence allows access for one approach leg to enter the circulating carriageway during a single phase with the U-turn movements being subject to a red signal within the circulating carriageway. Due to the small demand for this movement storage is provided within the circulating carriageway.

The pedestrian movement to the right of the entering leg is phased green within this phase when pedestrian demand is needed. Pedestrians and cyclist are able to walk to their desired exit path within the central island and cross again when the corresponding phase is available.

Pedestrian movement timings from (Akçelik & Associates 2001) are based on a recommended walking time of 1.0 and 1.2m/s corresponding to the 5th and 15th percentile speeds, respectively. This represents that 15% of all pedestrians recorded moved slower than the 1.2m/s speed and 5% moved slower than 1m/s.

On transition between phases the stored U-turn movements within the circulating carriageway are located ahead of the next entering phase and are able to complete their desired movement whilst the next entering phase approaches.

Due to the rotation of the phase in a counter-clockwise manner, the geometry of the roundabout is able to be utilised in such a way that vehicles can still be using the intersection whilst the next phase can proceed. The majority of vehicles that will be travelling whilst the following phase has been activated will be the right turn movements as these require the longest travel times due to the geometric delay.

The UK general phasing technique will be analysed as well to determine the capacities it is able to handle before reaching capacity. The general approach of the UK phasing can be seen diagrammatically in Appendix D and is discussed in section 3.2.2.

4.4.1 Signal Controller Settings

Signal controller settings for the phase sequence have been based on the Austroads (2003, Table C.2) guidelines and are shown below in Table 4.2

Table 4.2 – Austroads Signal Controller Settings

	Through and Left-Turn Movements (s)	Arrow-Controlled Right-Turn Movements (s)	Pedestrian Settings (s)
Minimum Green	5 – 10	5 – 6	
Yellow Time	3.0 – 5.0	3.0 to 6.0	
All-Red Time	1.0 – 3.0	1.0 – 3.0	
Walk Time			5 – 16
Clearance Time			6 – 20

The all-red time or red clearance time is used between the end of the yellow phase for the preceding signal phase and the beginning of the green on the next phase. Austroads (2003) states that the purpose of the all-red interval is to provide a safe clearance for vehicles that cross the stop line towards the end of the yellow interval since they may be in danger of collision with vehicles or pedestrians released in the following phase or signal group.

An all-red clearance time of 2 seconds will be assessed to comply with this table, however due to the geometry of a signalised roundabout it is likely that a clearance time of 0 seconds would be applied for the standard phasing technique as there is no distance a vehicle is required to cross before the following phase can proceed.

Figure 4.4 taken from Austroads (2003) shows the all-red clearance time as a function of speed and clearance distance. This will be used as a basis in providing an appropriate all-red interval time for the UK phasing technique due to clearance times of entering vehicles conflicting with green phase of the inner lane storage vehicles.

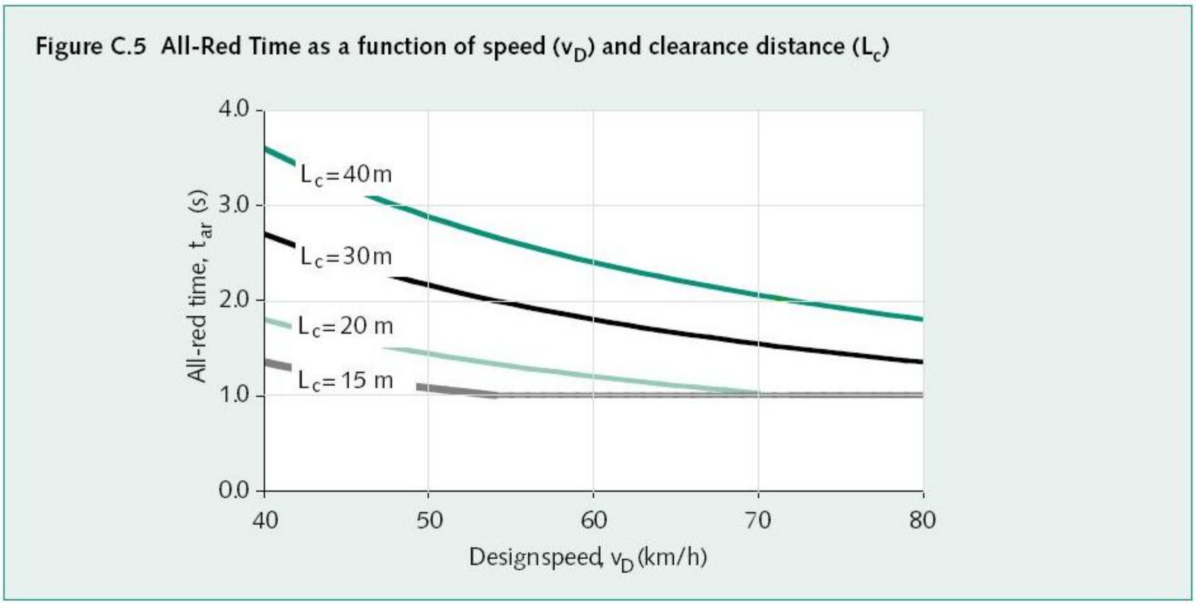


Figure 4.4 – All-red time as a function of speed and clearance distance (Austroads 2003, Figure C.5)

This is subject to the all-red time being greater than one second in length.

4.5 Inscribed diameters of existing two lane roundabouts in NSW, Australia

Current standards (Austroads 2011) used by the Roads and Maritime Services NSW state that a desirable minimum of 40m be used for the inscribed diameter for a two lane roundabout, when the largest design vehicle using the intersection is a 26.0m B-Double.

Three areas within New South Wales, Australia have been chosen as a sample set to determine the average size used for two lane rural / urban roundabouts. These areas include:

- Newcastle / Hunter Valley Region
- Central Coast
- Grafton

Represented in Figure 4.5 and Table 4.3 are the roundabout locations and diameters within the Newcastle/Hunter Region that represent a four leg two lane roundabout.

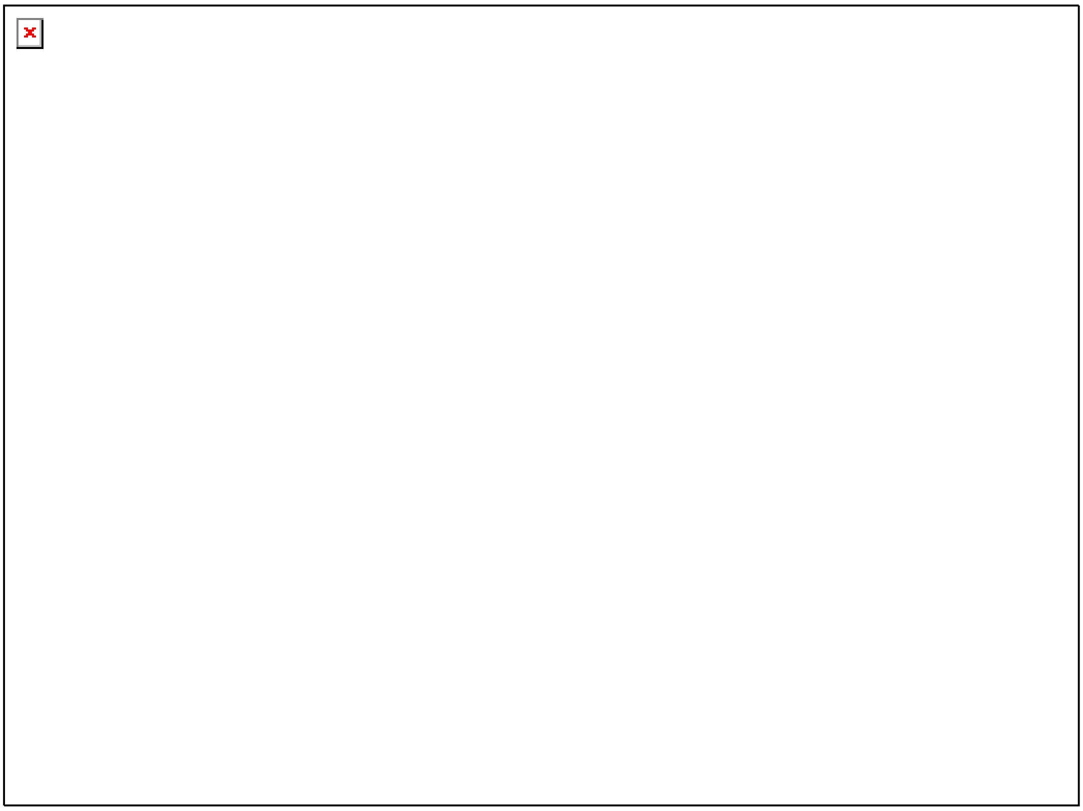


Figure 4.5 – Newcastle/Hunter Valley existing roundabout locations

Table 4.3 –Newcastle/Hunter Valley inscribed diameters

Newcastle / Hunter Valley		
No.	**Location**	**Diameter**
1	Five Islands Road & The Esplanade, Speers Point	53m
2	Lake Road & Frederick Street, Glendale	58m
3	Newcastle Link Road & Unclassified Road, Wallsend	68m
4	Newcastle Link Road & Lake Road, Wallsend	53m
5	Newcastle Link Road & Cameron Park Drive, Cameron Park	68m
6	George Booth Drive & Cameron Park Drive, Cameron Park	50m
7	Hannell Street & Branch Street, Wickham	52m
8	Industrial Drive & Elizabeth Street, Tighes Hill	63m
9	Teal Street & Fullerton Cove Road, Fern Bay	60m
10	Teal Street & Cabbage Tree Road, Fullerton Cove	57m
11	F3 Freeway & Pacific Highway, Blackhill	57m
12	Pacific Highway & Adelaide Street, Heatherbrae	85m
13	New England Highway & Racecourse Road, Rutherford	50m
14	New England Highway & Shipley Drive, Rutherford	60m

Represented in Figure 4.6 and Table 4.4 are the roundabout locations and diameters within the Central Coast Region that represent a four leg two lane roundabout.

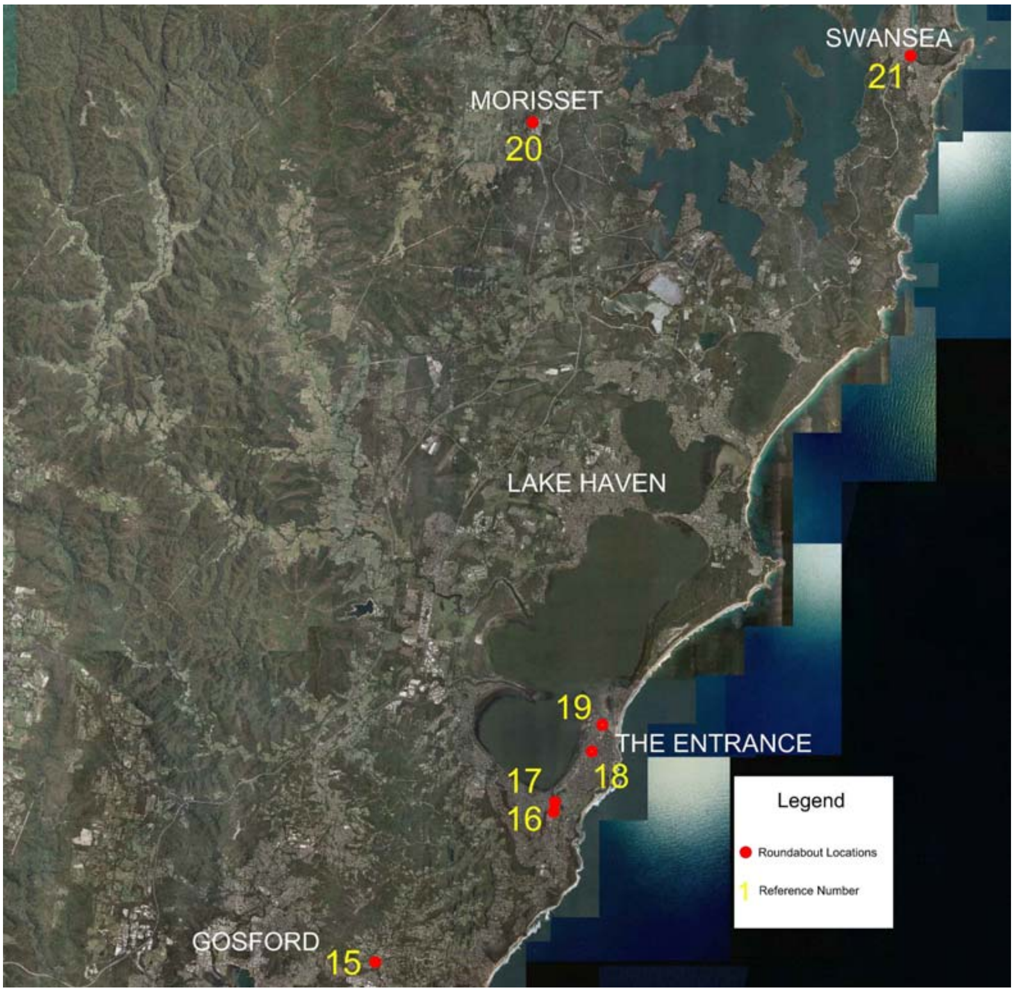


Figure 4.6 – Central Coast existing roundabout locations

Table 4.4 –Central Coast inscribed diameters

Central Coast		
No.	**Location**	**Diameter**
15	The Entrance Road & Carlton Road, Erina Heights	37m
16	The Entrance Road & Eastern Road, Bateau Bay	43m
17	The Entrance Road & Wyong Road, Bateau Bay	45m
18	The Entrance Road & Oakland Avenue, The Entrance	32m
19	The Entrance Road & Coral Street, The Entrance	32m
20	Mandalong Road & Gateway Boulevard, Morisset	50m
21	Pacific Highway & Bowman Street, Swansea	50m

The roundabouts stated in Table 4.3 that are below an inscribed diameter of 40m (15, 18 and 19) are typically found in an urban environment. As this report is more focused on a rural environment, inscribed diameters lower than 40m will be disregarded as it is not desirable, according to NSW road standards.

Represented in Figure 4.7 and Table 4.5 are the roundabout locations and diameters within the Grafton Region that represent a four leg two lane roundabout.

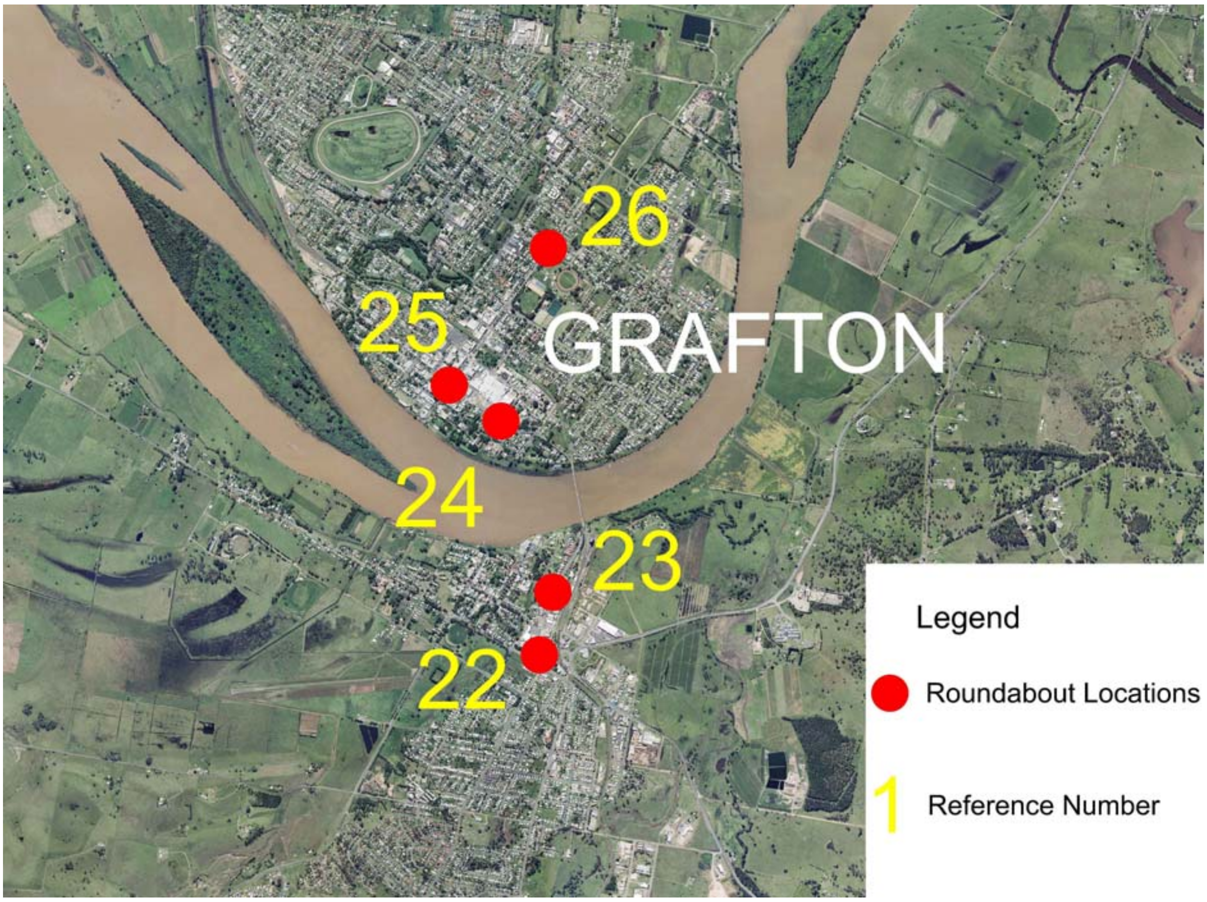


Figure 4.7 – Grafton existing roundabout locations

Table 4.5 –Grafton inscribed diameters

Grafton		
No.	**Location**	**Diameter**
22	Summerland Way & Ryan Street, Grafton	38m
23	Summerland Way & Through Street, Grafton	34m
24	Pound Street & Duke Street, Grafton	40m
25	Summerland Way & Fitzroy Street, Grafton	34m
26	Summerland Way & Pound Street, Grafton	38m
27	Summerland Way & Dobie Street, Grafton	40m

After assessment of the roundabout diameters across the three sample areas it can be seen that the majority of two lane roundabout diameters range from 40m to 60m in diameter. Diameters smaller than 40m are typically found in a more urban environment and roundabouts with a diameter larger than 60m are typically found at rural locations at the end of major freeway / highway roads.

This report will assess two roundabout models based on a 50m and 60m inscribed diameter to represent a common two lane rural roundabout example.

4.6 Field Research

Field research was conducted to determine Australian driver characteristics for key variables such as geometric delay and headway times which are heavily influenced on driver behaviour. These variables were measured at existing locations within the Newcastle and Hunter Region.

4.6.1 Geometric Delay

Geometric delay travel times were observed at two existing 52m and 63m inscribed diameter roundabouts, these observations will be used as a basis for the geometric delay data input within the computer modelling.

Each turn movement was observed from specific locations shown in Figures 4.8 and 4.9 for the 52m and 63m inscribed diameter roundabouts respectively. The travelling time for the vehicle entering and exiting the roundabout was recorded using a standard stopwatch.

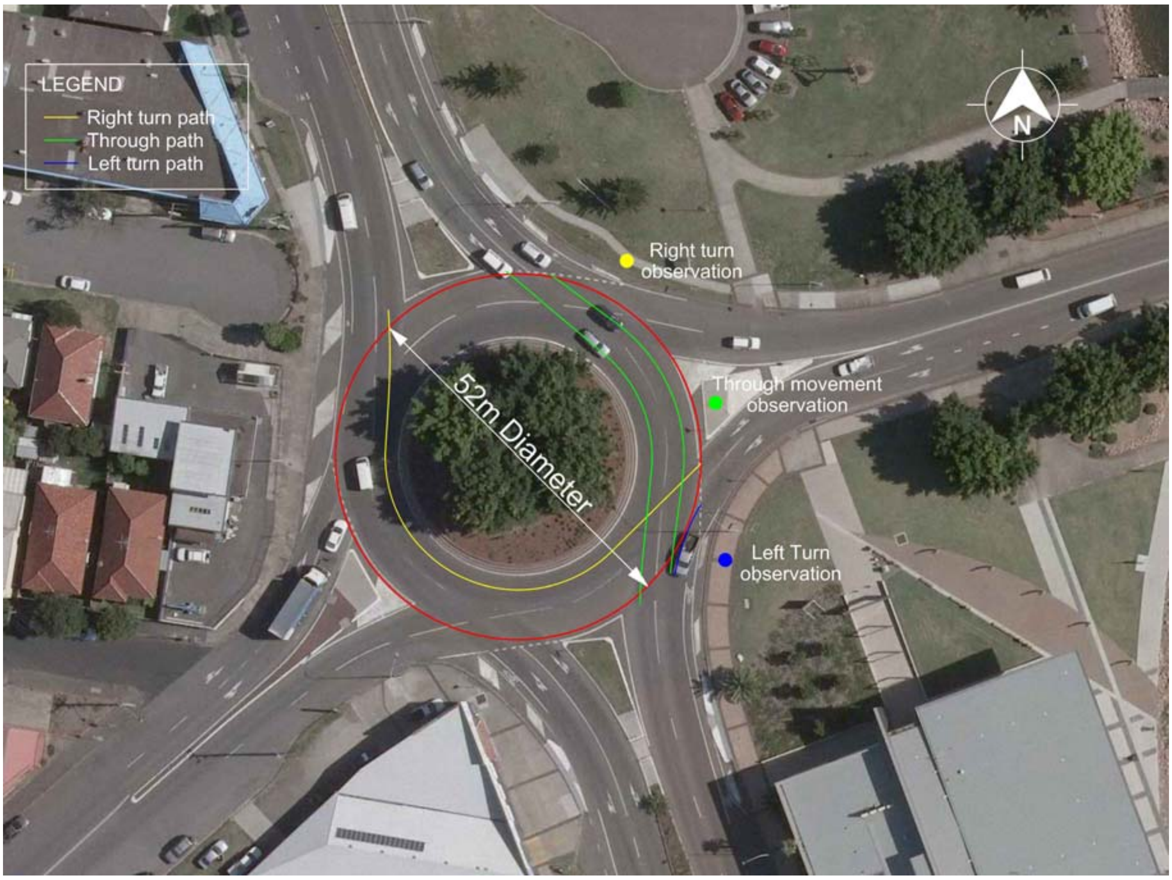


Figure 4.8 – Geometric delay observations 52m inscribed diameter roundabout

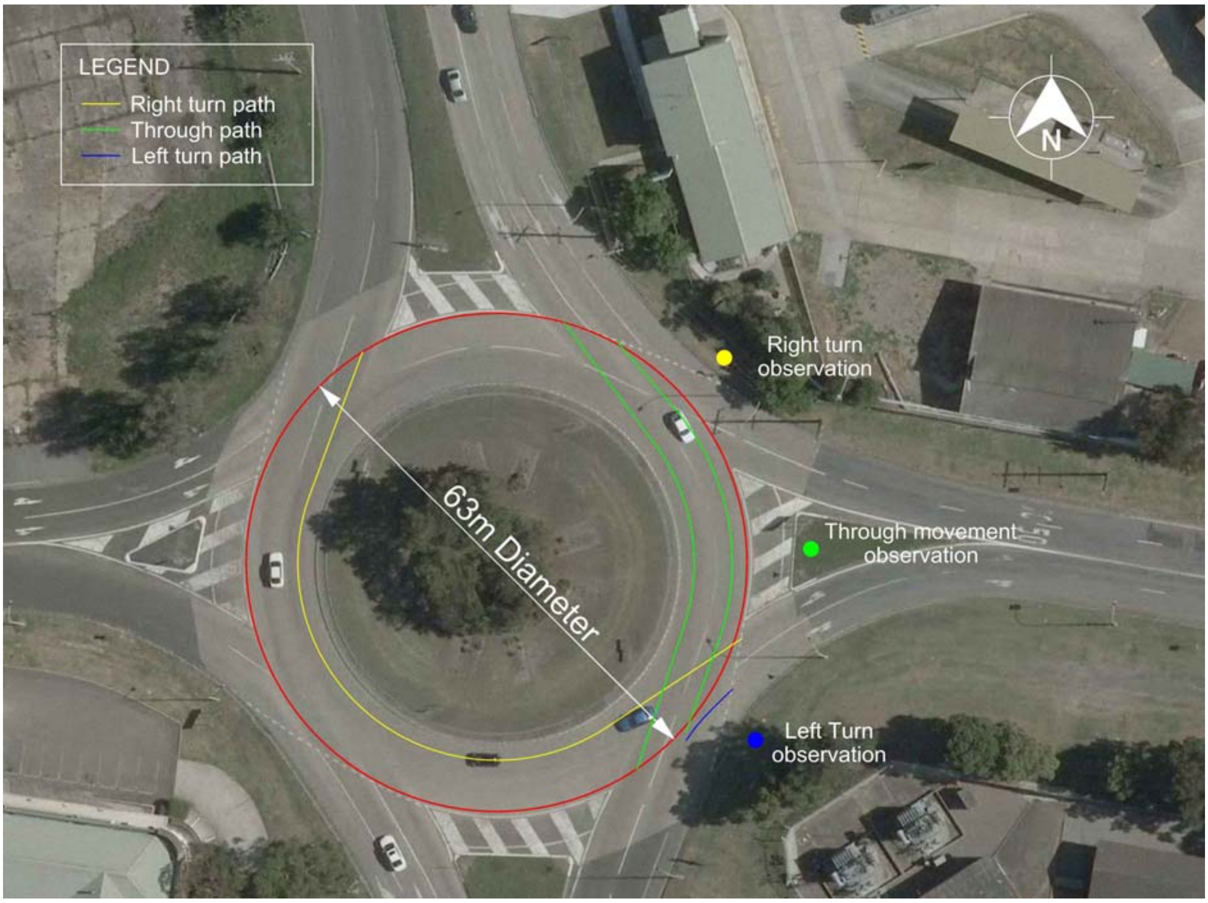


Figure 4.9 – Geometric delay observations 63m inscribed diameter roundabout

The travel lengths and average travel times for the 52m inscribed diameter roundabout based on a large car are shown in Table 4.6. The data sheets used to determine this average can be found in Appendix C.

Table 4.6 – Average cruise speed and geometric delay for a 52m inscribed diameter roundabout

52m Inscribed Diameter			
Movement	**Distance (m)**	**Average Cruise Speed (km/h)**	**Average Geometric Delay (s)**
Left turn movement	12	13.09	3.30
Through movement	53	26.34	7.24
Right turn movement	83	25.68	11.64

The travel lengths and average travel times for the 63m inscribed diameter roundabout based on a large car are shown in Table 4.7. The data sheets used to determine this average can be found in Appendix C.

Table 4.7 – Average cruise speed and geometric delay for a 63m inscribed diameter roundabout

63m Inscribed Diameter			
Movement	**Distance (m)**	**Average Cruise Speed (km/h)**	**Average Geometric Delay (s)**
Left turn movement	19	16.33	4.19
Through movement	60	27.91	7.74
Right turn movement	102	25.79	14.24

It is to be noted that each result recorded was uninfluenced by on coming vehicles that may cause the vehicle to increase in acceleration when entering the roundabout. This is to reflect signalised conditions where a vehicle will not be forced to identify a suitable gap to enter the roundabout, but will enter under a prioritised green phase during the signalised cycle time.

When entering this parameter into the LinSig models it will be entered based on average cruise speeds and based on a distance that corresponds to the current standards (Austroads 2011) used in NSW for the corresponding inscribed diameter.

Distances for the corresponding movements and inscribed diameters based on the current Austroad standards using a 50m entry and 100m exit curves are shown in Table 4.8.

Table 4.8 – Distances of various turning movements for the corresponding roundabout diameters based on Austroad standards

50m Inscribed Diameter		60m Inscribed Diameter	
Movement	**Distance (m)**	**Movement**	**Distance (m)**
Left turn movement	12	Left turn movement	19
Through movement	47	Through movement	63
Right turn movement	76	Right turn movement	98

4.6.2 Queue Discharge Headways

Queue discharge headway is a key variable when determining how many vehicles are able to enter the roundabout under a green phase. Field tests were conducted to determine Australian driver behaviour characteristics for this variable to develop a more accurate capacity model.

The site shown below in Figure 4.10 was chosen to determine the headways of a lane subjected to signals in a semi-rural/urban environment under highway conditions. The site was chosen as it is subjected to congestive flows around peak periods, and is located on a 0% grade.

To determine the average headway for vehicle movements only the queued vehicles stored prior to the green phase were counted. This was done to disregard random arrival times which would increase headway times and give inaccurate results. As this report is interested in the capacity of the intersection, headway times from a stored queue is vital to determine the capacity of vehicles that can travel through a green phase.

Figure 4.10 – Test sites to determine headway and saturation flow through signals, semi rural urban environment East Maitland.

Table 4.9 – Headway and saturation flow data East Maitland site

Date	29/08/2012	**Time**	16:30 to 17:30	
Location	East Maitland	**Weather**	Fine	
TEST SITE 1				
Test	**Time (s)**	**Number of Vehicles**	**Headway (s)**	**Saturation flow (veh/hr)**
1	27.6	14	1.97	1826
2	24.5	12	2.04	1763
3	26.0	13	2.00	1800
4	21.0	12	1.75	2057
5	20.8	10	2.08	1731
6	20.6	9	2.29	1573
7	26.4	14	1.89	1909
8	25.5	13	1.96	1835
9	22.4	12	1.87	1929
10	23.8	12	1.98	1815
11	19.8	10	1.98	1818
12	23.4	12	1.95	1846
13	26.1	13	2.01	1793
14	18.9	10	1.89	1905
15	19.2	10	1.92	1875
16	22.3	11	2.03	1776
17	22.8	11	2.07	1737
18	16.8	9	1.87	1929
19	19.2	10	1.92	1875
20	21.8	11	1.98	1817
		Average	**1.97**	**1830**

Date	30/08/2012	**Time**	16:30 to 17:30	
Location	East Maitland	**Weather**	Fine	
TEST SITE 2				
Test	**Time (s)**	**Number of Vehicles**	**Headway (s)**	**Saturation flow (veh/hr)**
1	10.8	5	2.16	1667
2	19.1	9	2.12	1696
3	17.2	8	2.15	1674
4	14.1	6	2.35	1532
5	19.5	9	2.17	1662
6	22.5	11	2.05	1760
7	22.5	12	1.88	1920
8	19.8	10	1.98	1818
9	17.0	8	2.13	1694
10	16.8	8	2.10	1714
11	18.8	9	2.09	1723
12	14.8	7	2.11	1703
13	14.6	7	2.09	1726
14	20.2	10	2.02	1782
15	22.8	12	1.90	1895
16	18.6	9	2.07	1742
17	13.4	6	2.23	1612
18	20.4	10	2.04	1765
19	19.5	10	1.95	1846
20	16.8	8	2.10	1714
		Average	**2.08**	**1732**

The average headway for the through movement (test site 1) for this site was 1.97 seconds which equals to a lane saturation flow of 1830 veh/hr. The average headway time for the right turn movement (test site 2) was a bit larger at 2.08 seconds giving a lane saturation value of 1732 veh/hr. The right turn movement seemed to incur a larger headway time due to the driver’s caution when navigating the movement.

The site shown below in Figure 4.11 was chosen to determine the queue discharge headway of a lane subjected to signals in an urban environment. The site was chosen as it is subjected to congestive flows around peak periods, low heavy vehicle traffic and is located on a 0% grade.

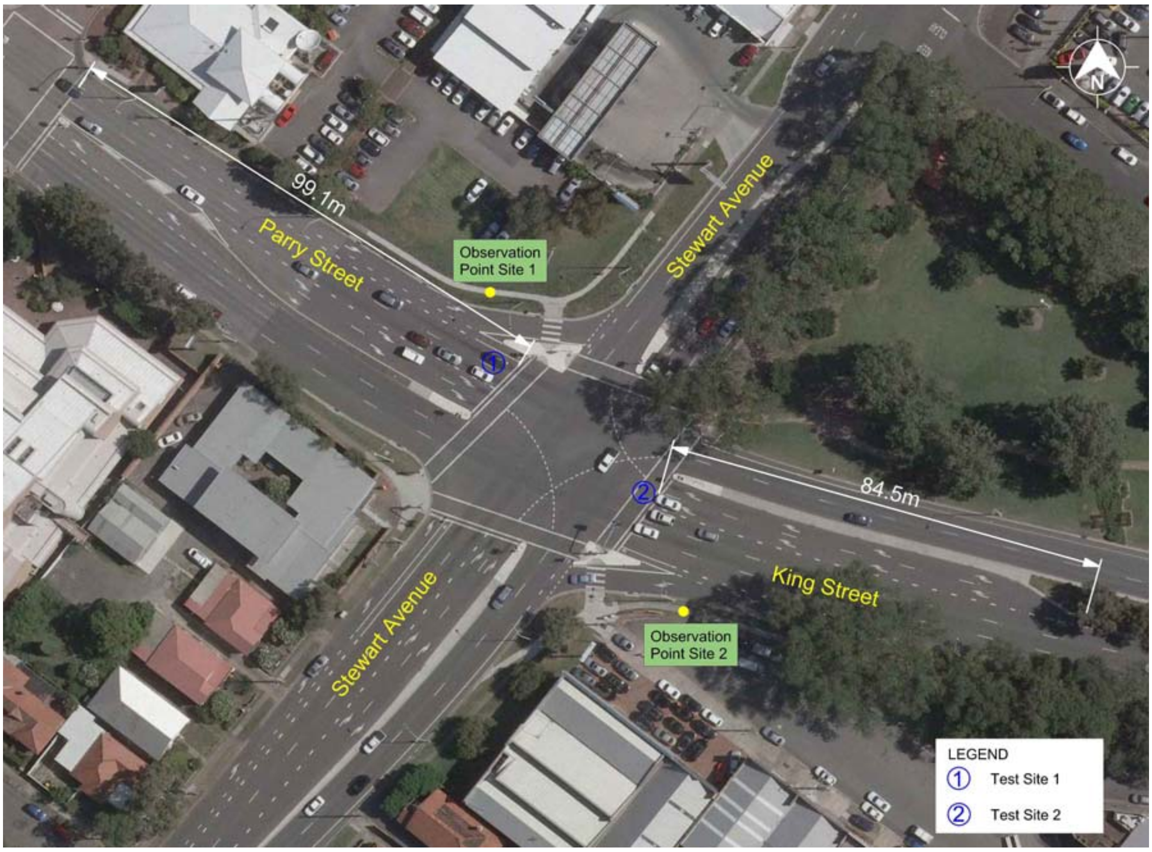


Figure 4.11 – Test sites to determine headway and saturation flow through signals, urban environment Newcastle.

Shown in Table 4.10 is the queue discharge headway data taken for the urban Newcastle site. The average headway for a through movement (test site 1) was calculated to be 1.89 seconds which equals to a saturation flow of 1903 veh/hr. The average headway time for the right turn movement (test site 2) was a bit larger at 1.92 seconds giving a lane saturation value of 1878 veh/hr.

Table 4.10 – Headway and saturation flow data Newcastle site

Date	6/08/2012		**Time**	08:00 to 09:00
Location		Newcastle	**Weather**	Fine
TEST SITE 1				
Test	**Time (s)**	**Number of Vehicles**	**Headway (s)**	**Saturation flow (veh/hr)**
1	18.9	10	1.89	1905
2	21.8	11	1.98	1817
3	21.0	11	1.91	1886
4	20.9	11	1.90	1895
5	15.5	8	1.94	1858
6	18.2	9	2.02	1780
7	25.6	14	1.83	1969
8	16.4	9	1.82	1976
9	23.1	13	1.78	2026
10	26.4	14	1.89	1909
11	23.4	13	1.80	2000
12	21.2	11	1.93	1868
13	19.0	10	1.90	1895
14	15.3	8	1.91	1882
15	17.9	9	1.99	1810
16	17.2	9	1.91	1884
17	23.3	13	1.79	2009
18	17.5	9	1.94	1851
19	21.0	11	1.91	1886
20	25.8	14	1.84	1953
		Average	**1.89**	**1903**

Date	8/08/2012		**Time**	16:30 to 17:30
Location		Newcastle	**Weather**	Fine
TEST SITE 2				
Test	**Time (s)**	**Number of Vehicles**	**Headway (s)**	**Saturation flow (veh/hr)**
1	15.9	8	1.99	1811
2	9.4	5	1.88	1915
3	18.1	10	1.81	1989
4	19.4	10	1.94	1856
5	16.9	9	1.88	1917
6	17.4	9	1.93	1862
7	15.7	8	1.96	1834
8	13.8	7	1.97	1826
9	13.4	7	1.91	1881
10	17.0	9	1.89	1906
11	18.5	10	1.85	1946
12	18.6	10	1.86	1935
13	19.4	10	1.94	1856
14	15.5	8	1.94	1858
15	16.0	8	2.00	1800
16	17.3	9	1.92	1873
17	18.8	10	1.88	1915
18	17.4	9	1.93	1862
19	17.8	9	1.98	1820
20	13.3	7	1.90	1895
		Average	**1.92**	**1878**

The lane saturation flows between the two locations differ fairly significantly between the corresponding movements. For the through movement the difference between locations is 73 veh/hr and for the right turn movements it is 146 veh/hr.

This difference may correspond to the driving environment, as in an urban environment vehicles may be more used to signalised intersections and driving more closely behind vehicles leading to a decreased headway and an increased saturation flow. Another observation made was that within the urban location the road fleet was generally made up of smaller vehicles that were able to accelerate more quickly than other larger vehicles such as four wheel drives which were more common on the East Maitland site.

The implications from these test show that it may be necessary to provide different models to accurately evaluate the capacity of a roundabout depending on its intended location. When evaluating the existing roundabout locations from section 4.5 of this report, it can be seen that the majority of roundabouts are located in a semi-rural environment. This environment is better represented by the test location conducted in East Maitland which represents a semi rural highway intersecting with a major local road.

Due to these findings two models will be analysed to evaluate the differing capacities due to the location of the roundabout. One model will represent the **semi-rural/urban environment** which will have a queue discharge lane saturation flow of **1800 veh/hr**. The other will represent an **urban environment** which will have a queue discharge lane saturation flow of **1900 veh/hr.**

The lane saturation flows were weighted more heavily to the through movement test values (test site 1) than the right turn movements (test site 2), conducted at the signalised junctions as the entering movement into a roundabout intersection is not as severe as the right turn movements tested.

The saturation flows for the left turn movement is also expected to be greater than the recorded average saturation flow of 1732 & 1878 veh/hr for the right turn movements. This is due to the geometry of the left turn movement at a roundabout not being as severe as the right turn movement at a signalised junction. Therefore it is expected that the saturation flow will more closely resemble that of a through movement.

4.7 Implications/Consequential Effects

4.7.1 Safety

The safety implications of the project are onsite field testing of follow-up headways. Each specified site will have to be assessed to Roads and Maritime Services (RMS) requirements. This involves a risk assessment of each site prior to commencement of survey to eliminate any risks of injury sustained while gathering information under live traffic.

In relation to the aims and objectives of the project itself, the safety implications can be beneficial to the community due to the safety benefits of signalisation of roundabouts towards cyclists and pedestrians. Also with the signalisation of roundabouts it eliminates drivers running the risk of entering under undesirable critical gap times which can lead to accidents.

Instead of current trends of replacing un-signalised roundabouts that have exceeded their intended capacity into standard signalised traffic control sites that allow high angle collisions, these existing roundabouts can be retro-fitted with signals which allows a safer and more sustainable outcome for traffic.

4.7.2 Sustainability

Due to the large reliance on transport worldwide the benefits in determining sufficient intersection treatments can have a significant impact on the sustainability of the road network. Engineers today are responsible for designing for the future and being sustainable so the impact of being able to retrofit existing un-signalised roundabouts with signalisation that may increase the design life for years to come can have great benefits.

Increasing the capacity of an intersection can have a positive impact on the reduced emissions of vehicles that would occur if they were forced to wait in queues stopping and starting for extended periods of time. Also being able to retrofit existing roundabouts provides minimal impact on the surrounding environment when a new intersection such as grade separated interchange may be thought to be necessary.

This report will determine whether these issues will be able to be addressed through the implementations of signalised roundabouts.

5. LINSIG MODELS

Signalised roundabout models were set up in LinSig based on the variables determined from both field research and research conducted worldwide. These models were then applied with uniform traffic flows to determine when a section or the intersection as a whole reaches capacity.

Variables such as the cruise speed of a vehicle and distance of the vehicle path around the roundabout are put into the LinSig model by the lane connecters which join each specified lane. The saturation flow, lane widths and phase sequence variables are determined from the information placed in the lane component of the model. All the other parameters are set up in their own specific area within the LinSig program.

Due to the variability of phase sequences that can be applied to a signalised roundabout the capacities for both the general phase sequence used in the UK and the one specified in section 4 (standard phasing) will be determined for the capacity of a signalised roundabout.

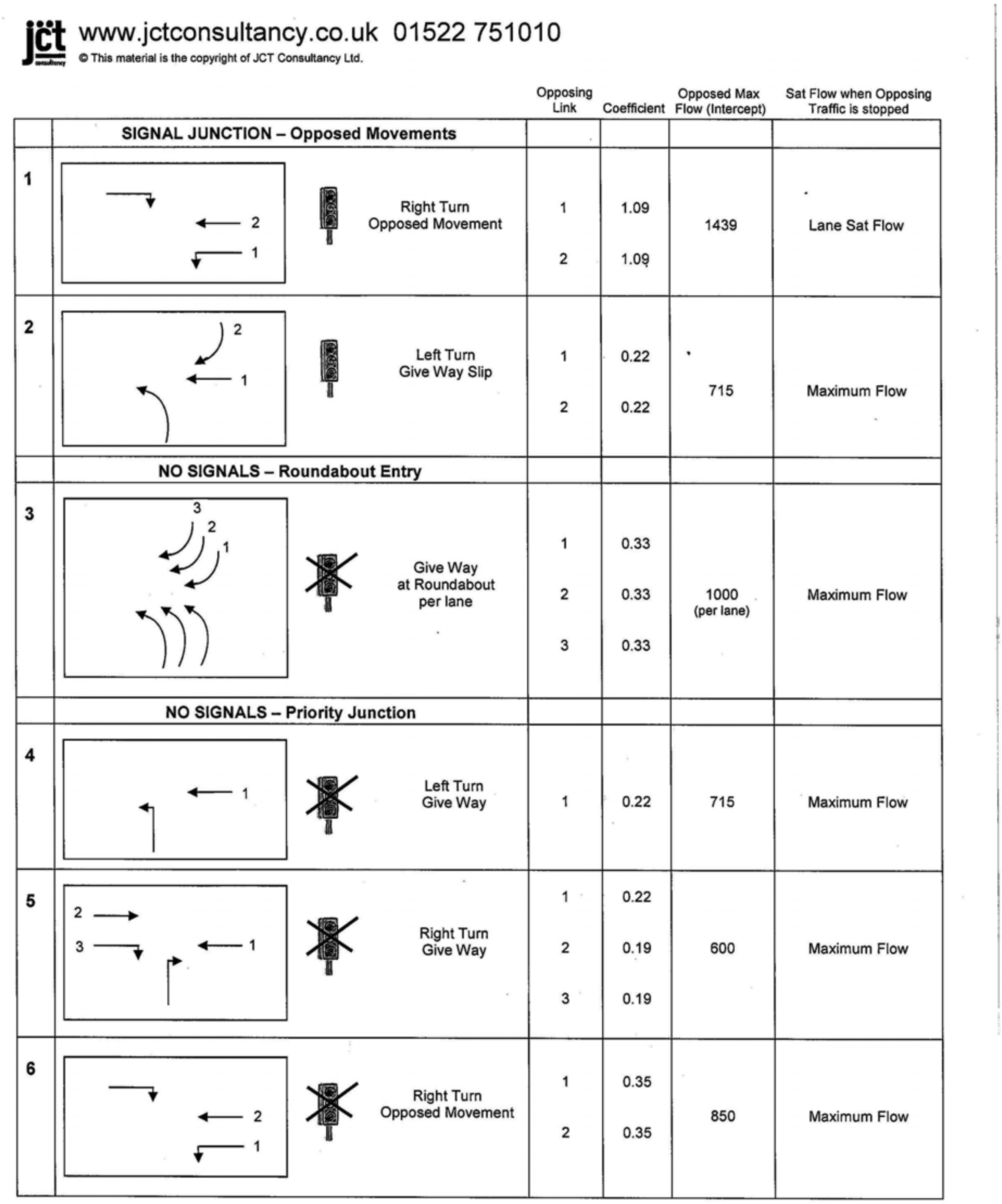
The un-signalised model was developed using saturation flows based on the UK TRL method which determine that a saturation flow of 1000 veh/hr is to be used for a give way junction at a roundabout. A coefficient of 0.33 is used as the intercept value for the opposing circulating carriageway flow to determine when a vehicle will enter the roundabout.

These values stated above are used in standard modelling practice within the UK by the developers of the LinSig program. The saturation flows and coefficients for opposed movements developed by JCT Consulting is shown in Figure 5.1.

This method does not take driver behaviour into account and when modelled using the above mentioned values it provides a total capacity value of 4800 veh/hr. This is unrealistic as it represents an ideal case where all traffic volumes are working in complete unison and does not reflect real life conditions.

Due to this the un-signalised LinSig models will not be included for evaluation. Therefore the capacities of the signalised models that are determined will be compared to research conducted by HCM (2010) and Tan (2001) for comparison to an un-signalised situation.

Shown in the following sections are diagrammatic views of the LinSig models



		Opposing Link	Coefficient	Opposed Max Flow (Intercept)	Sat Flow when Opposing Traffic is stopped
	SIGNAL JUNCTION – Opposed Movements				
1	Right Turn Opposed Movement	1 2	1.09 1.09	1439	Lane Sat Flow
2	Left Turn Give Way Slip	1 2	0.22 0.22	715	Maximum Flow
	NO SIGNALS – Roundabout Entry				
3	Give Way at Roundabout per lane	1 2 3	0.33 0.33 0.33	1000 (per lane)	Maximum Flow
	NO SIGNALS – Priority Junction				
4	Left Turn Give Way	1	0.22	715	Maximum Flow
5	Right Turn Give Way	1 2 3	0.22 0.19 0.19	600	Maximum Flow
6	Right Turn Opposed Movement	1 2	0.35 0.35	850	Maximum Flow

Figure 5.1 – Saturation flows and coefficients for opposed movements developed by JCT Consulting

5.1 Signalised Roundabout 50m diameter

The 50m roundabout models have been modelled using the parameters measured in the field research to determine the effective capacities of the intersection. Two phasing structures have been modelled, one which is based on standard traffic controlled signal (TCS) site practices currently used in Australia and the other more complex phasing structure used in the United Kingdom.

The 50m inscribed diameter roundabout geometry details developed, based on Austroads (2011) standards are shown in Table 5.1. These values are developed based on a 50m entry radius and a 100m exit radius. The design vehicle used is a 26.0m B double.

Table 5.1 – 50m Inscribed diameter geometric elements

ELEMENT	LENGTH (m)	CRUISE SPEEDS (km/h)
Entry Radius	50	
Exit Radius	100	
Left Turn Travel Distance	12	13
Through Movement Travel Distance	47	26
Right Turn Travel Distance	76	26
Inner lane Storage	14	

5.1.1 Standard Phasing

This phasing structure is a simplistic method where one leg is signalised green and the other three legs are stopped in the red phase. This can be represented in LinSig typically as a standard four way traffic controlled signal site as shown in Figure 5.2, however special consideration needs to be taken into account for U-turn movements.

If U-turn movements exceed the capacity of the inner lane storage within the phase time, this will cause excessive delays due to the excess queues blocking access for right turn movements within the intersection. When this event happens it will cause the intersection to fail in handling capacities.

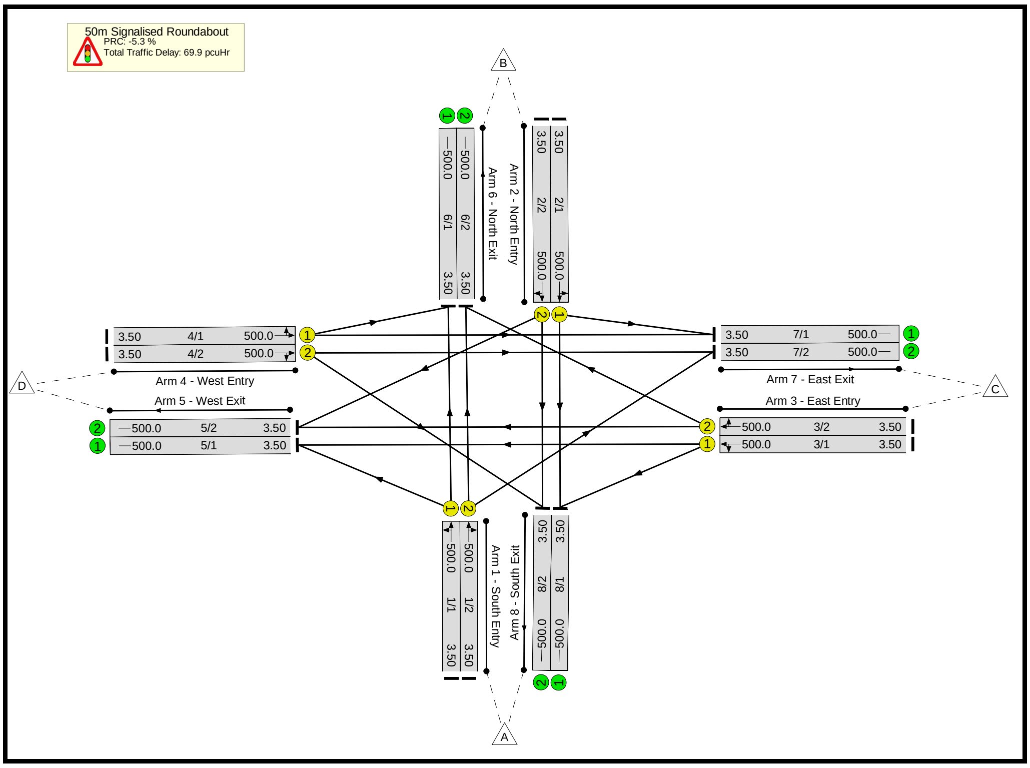


Figure 5.2 – 50m signalised roundabout LinSig Model – Standard phasing

Due to the geometry of the roundabout, variable all-red interval times can be taken into consideration depending upon the required safety wanted to be achieved by the governing authority. Due to this factor all-red clearance times stated in Table 5.2 will be assessed along with the governing reason.

Table 5.2 – All-red interval time for 50m inscribed diameter

All-red interval time (s)	Reason
2	To comply with the middle value of Table 4.2 requirements.
0	Allow clearance time based purely on geometric delay
-1	Allow clearance time based on a desirable 3 second clearance time provided by the geometric delay. This is based on a 35m distance to the conflict point and an average vehicle acceleration speed of 30km/h. The vehicle entry speed is based on saturated flows, thus taken from Appendix C values.

The yellow circles shown at the front of each entering lane represent that the lane is under signalised control. The green circles at the end of each exit lane show that the lane is uninterrupted and is able to be used at the lane saturation flow limit. The letters in the triangle shapes represent the origins/destinations of each vehicle for traffic flow input.

A 13 second minimum phase time will be used for any one stage to allow for sufficient time for pedestrians to complete the required 14m walking movement into the central median. This equates to a 1.08m/s walking time which falls between the recommended 1 to 1.2m/s walking time specified from (Akçelik & Associates 2001).

5.1.2 UK Phasing

The United Kingdom phasing structure is a bit more complex as it utilises its internal signals a lot more than the standard phasing structure. The phasing structure can be seen diagrammatically attached to Appendix D where the green lanes represent the lanes under a green phase and the red lanes represent the lanes under a red phase. Shown below in Figure 5.3 is the model developed in LinSig for this phasing structure.

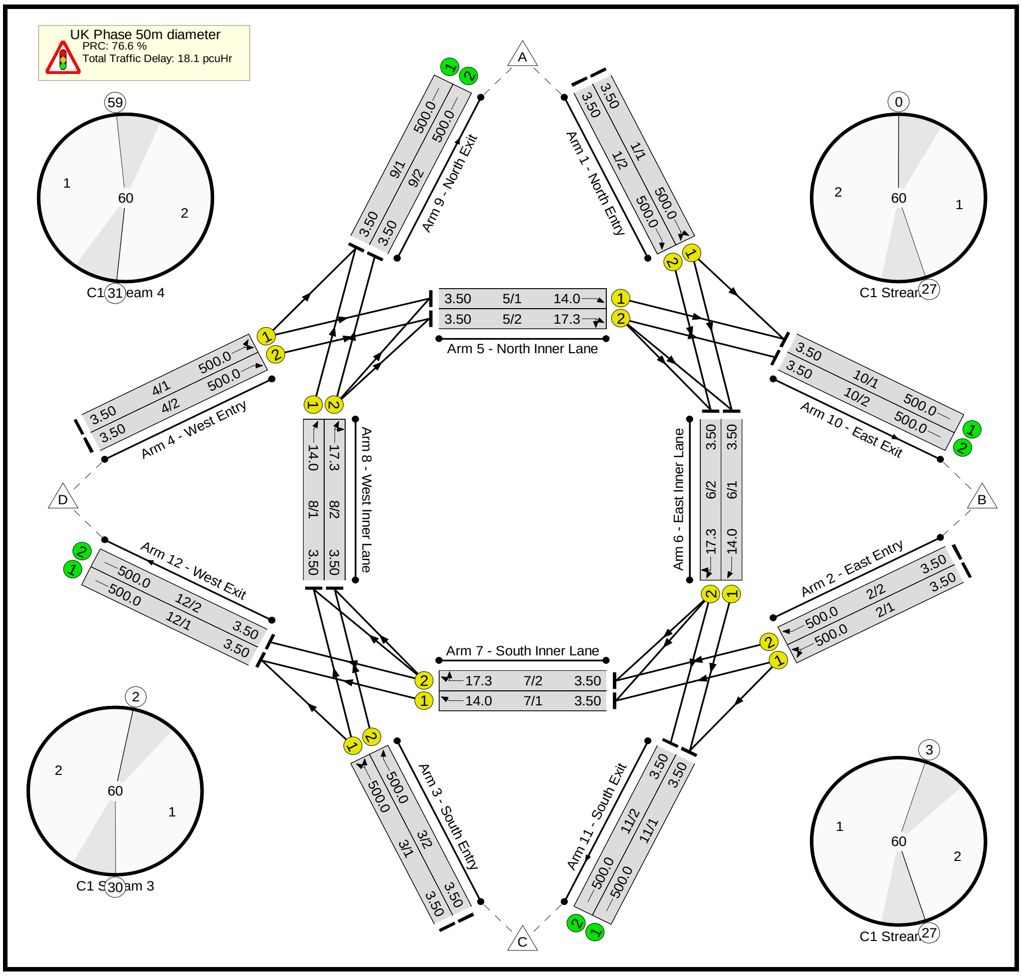


Figure 5.3 – 50m signalised roundabout LinSig Model – UK phasing

The yellow circles shown at the front of each entering lane represent that the lane is under signalised control. The green circles at the end of each exit lane show that the lane is uninterrupted and is able to be used at the lane saturation flow limit. The letters in the triangle shapes represent the origins/destinations of each vehicle for traffic flow input.

It is to be noted that this phasing structure has a heavy reliance on the inner lane storage. When the inner lane storage is exceeded it will cause the through movement to be blocked and will cause the intersection to fail. This requires right turn movements to be provided with short phase times to clear the circulating carriageway effectively.

A 2 second all-red interval will be provided based on Figure 4.4 as a minimum for conflicting flows that require an entry lane to clear before an inner lane is phased green. The conflicting flow requires an approximate 24m of clearance before the inner lane phase has a clear movement.

Also to be noted this phasing structure does not provide for pedestrians to gain access within the central median. Due to the short phase time required for the circulating carriageway to clear pedestrian movements do not have enough time to cross the exit lanes safely. For this reason pedestrian movements have not been considered in the UK phasing structure.

5.2 Signalised Roundabout 60m diameter

The 60m roundabout models have been modelled using the parameters measured in the field research to determine the effective capacities of the intersection. Two phasing structures have been modelled, one which is based on standard TCS site practices currently used in Australia and the other more complex phasing structure used in the United Kingdom.

The 60m inscribed diameter roundabout geometry details developed based on Austroads (2011) standards are shown in Table 5.3. These values are developed based on a 50m entry radius and a 100m exit radius. The design vehicle used is a 26.0m B double.

Table 5.3 – 60m Inscribed diameter geometric elements

ELEMENT	LENGTH (m)	CRUISE SPEEDS (km/h)
Entry Radius	50m	
Exit Radius	100m	
Left Turn Travel Distance	19m	16
Through Movement Travel Distance	63m	28
Right Turn Travel Distance	98m	26
Inner lane Storage	11m	

5.2.1 Standard Phasing

This phasing structure is a simplistic method where one leg is signalised green and the other three legs are stopped in the red phase. This can be represented in LinSig typically as a standard four way traffic controlled signal site as shown in Figure 5.4, however special consideration needs to be taken into account for U-turn movements.

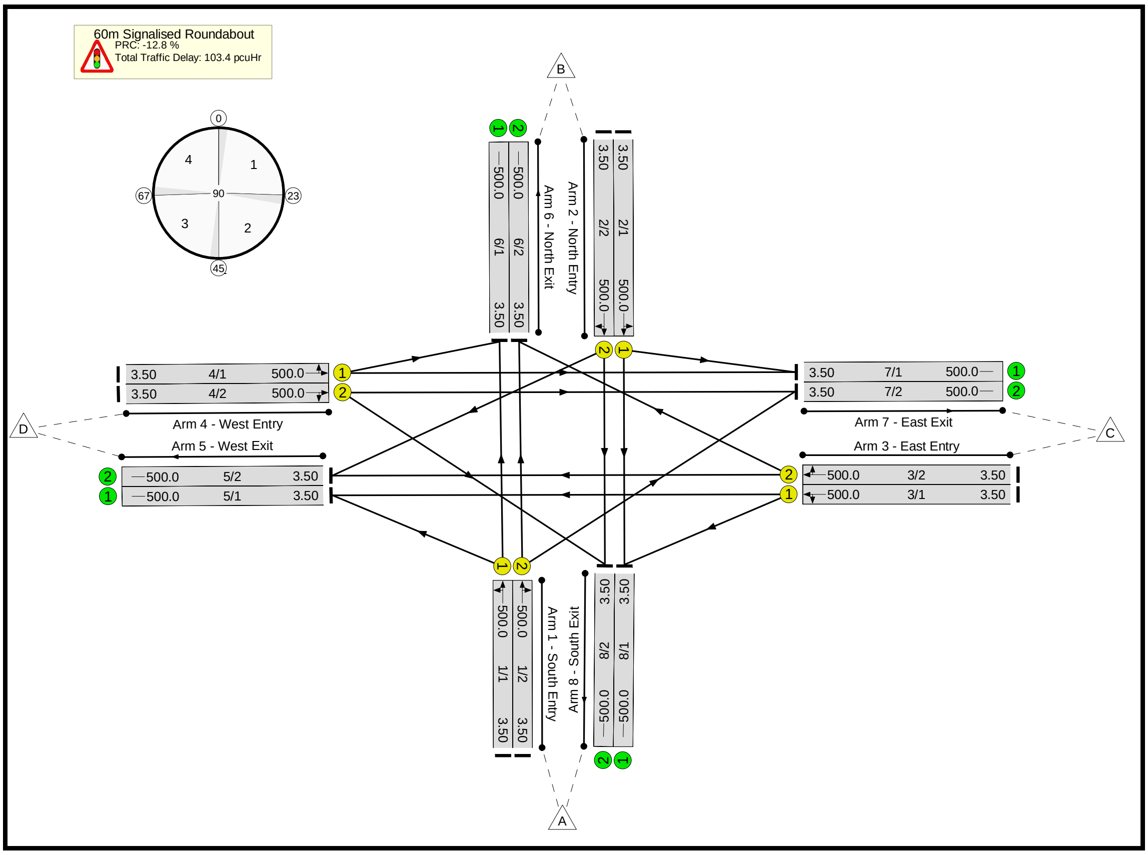


Figure 5.4 – 60m signalised roundabout LinSig Model – Standard phasing

If U-turn movements exceed the capacity of the inner lane storage within the phase time, this will cause excessive delays due to the excess queues blocking access for through movements within the intersection. When this event happens it will cause the intersection to fail in handling capacities.

Due to the geometry of the roundabout, variable all-red interval times can be taken into consideration depending upon the required safety wanted to be achieved by the governing authority. Due to this factor all-red clearance times stated in Table 5.4 will be assessed for the 60m inscribed diameter along with the governing reason.

Table 5.4 – All-red interval time for 60m inscribed diameter

All-red interval time (s)	**Reason**
2	To comply with the middle value of Table 4.2 requirements.
0	Allow clearance time based purely on geometric delay
-2	Allow clearance time based on a desirable 3 second clearance time provided by the geometric delay. This is based on a 43m distance to the conflict point and an average vehicle acceleration speed of 30km/h. The vehicle entry speed is based on saturated flows, thus taken from Appendix C values.

The yellow circles shown at the front of each entering lane represent that the lane is under signalised control. The green circles at the end of each exit lane show that the lane is uninterrupted and is able to be used at the lane saturation flow limit. The letters in the triangle shapes represent the origins/destinations of each vehicle for traffic flow input.

A 13 second minimum phase time will be used for any one stage to allow for sufficient time for pedestrians to complete the required 14m walking movement into the central median. This equates to a 1.08m/s walking time which falls between the recommended 1 to 1.2m/s walking time specified from (Akçelik & Associates 2001).

5.2.2 UK Phasing

The United Kingdom phasing structure is a bit more complex as it utilises its internal signals a lot more than the standard phasing structure. The phasing structure can be seen diagrammatically attached to Appendix D where the green lanes represent the lanes under a green phase and the red lanes represent the lanes under a red phase. Shown below in Figure 5.5 is the model developed in LinSig for this phasing structure.

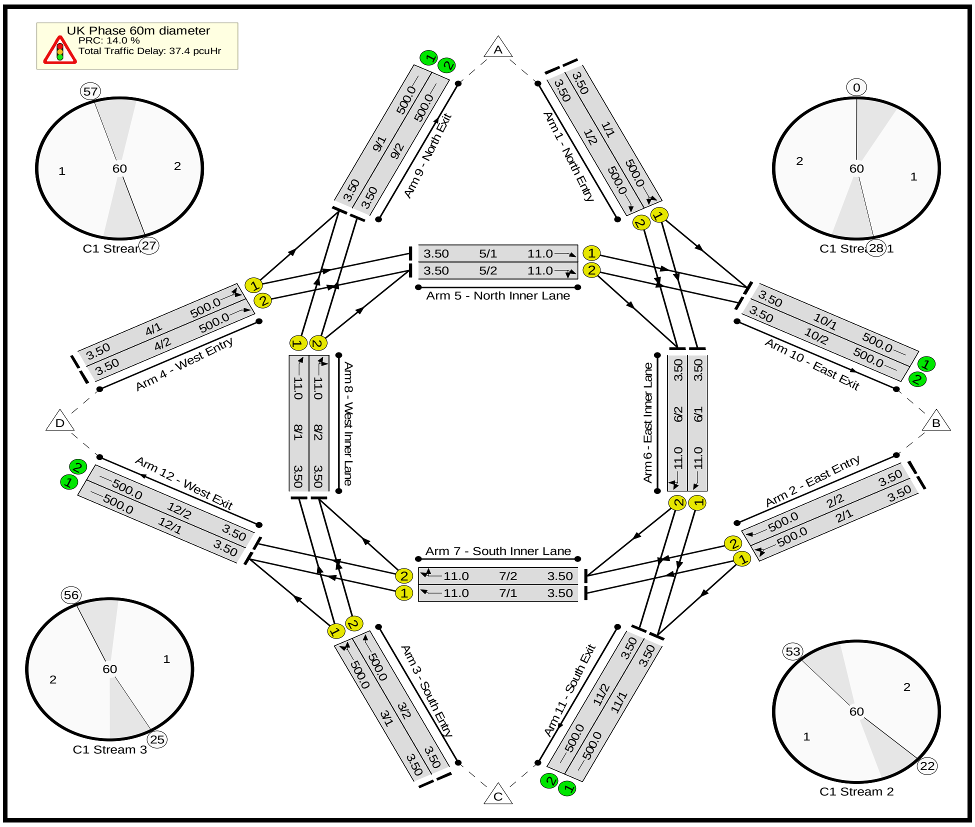


Figure 5.5 – 60m signalised roundabout LinSig Model – UK phasing

The yellow circles shown at the front of each entering lane represent that the lane is under signalised control. The green circles at the end of each exit lane show that the lane is uninterrupted and is able to be used at the lane saturation flow limit. The letters in the triangle shapes represent the origins/destinations of each vehicle for traffic flow input.

It is to be noted that this phasing structure has a heavy reliance on the inner lane storage. When the inner lane storage is exceeded it will cause the through movement to be blocked and will cause the intersection to fail. This requires right turn movements to be provided with short phase times to clear the circulating carriageway effectively.

A 2 second all-red interval will be provided based on Figure 4.4 as a minimum for conflicting flows that require an entry lane to clear before an inner lane is phased green. The conflicting flow requires an approximate 26m of clearance before the inner lane phase has a clear movement.

Also to be noted this phasing structure does not provide for pedestrians to gain access within the central median. Due to the short phase time required for the circulating carriageway to clear pedestrian movements do not have enough time to cross the exit lanes safely. For this reason pedestrian movements have not been considered in the UK phasing structure.

6. RESULTS

6.1 Signalised Roundabout 50m diameter

The results are combined into both standard phasing and UK phasing sections. For the standard phasing an excel spreadsheet has been developed to assess the capacity of the signalised roundabout intersection to compare with the LinSig models. The excel spreadsheet will also use the queue discharge values taken from the field tests and apply these to equations 3.3 to 3.5.

6.1.1 Standard Phasing

The capacity results are based on that the required U turn movements do not exceed the capacity of the inner lane storage length of 14m for the green phase period.

The right inner lane storage of 14m is found to be able to comfortably store two vehicles, but if necessary 3 vehicles can store within the limit of the 19m storage before impedance on a vehicles through movement. Two vehicles are also able to be stored in the left inner lane if required, the left lane will be assumed to be used if the right inner lane exceeds capacity within the green phase. This gives a total storage capacity of 5 passenger car units.

U turn movements were not modelled in as they will not impact on the capacity unless they exceed the values stated in Table 6.1.

Table 6.1 – Maximum U turn movements for 50m signalised roundabout

Cycle Time (s)	All-red interval (s)	Maximum U-turn movements (veh/hr)
60	2	1385
	0	1200
	-1	1125
75	2	1075
	0	960
	-1	911
90	2	878
	0	800
	-1	766
105	2	742
	0	686
	-1	661

6.1.1.1 Semi-rural / Urban Environment Saturation flow 1800 veh/hr

Case 1: 2 second all-red interval

A uniform traffic flow was entered into the LinSig model to determine the capacity of the signalised roundabout. The uniform traffic flows were increased until level of service F requirements were met from Table 3.7, with control delay of up to 80 seconds and a lane saturation of 100%.

Shown in Figure 6.1 are the total capacities for the signalised intersection based on different cycle times. The measure of the capacity here is the control delay requirements of 80s representing a level of service F. The data tables are attached to Appendix F in Tables F.1 to F.4.

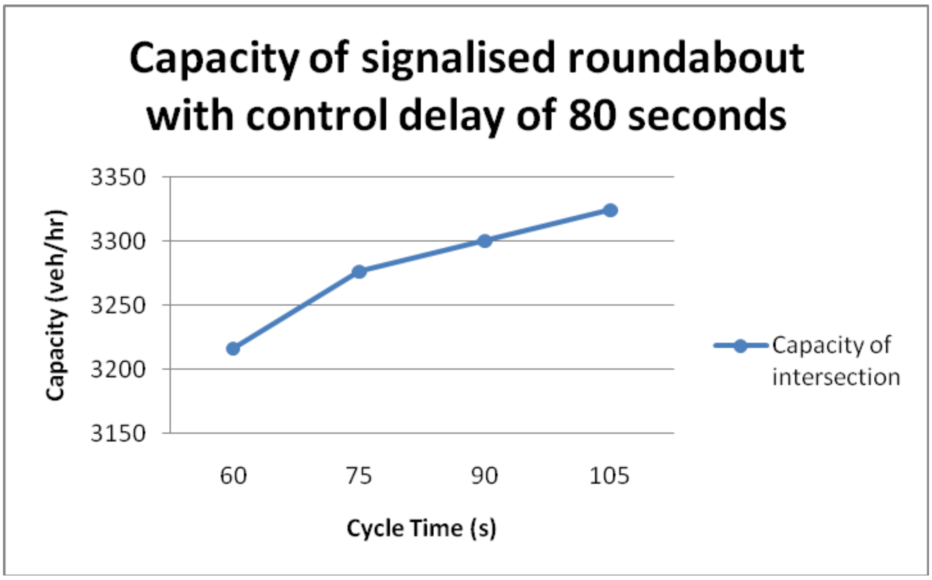


Figure 6.1 – Capacity of signalised roundabout based on 80 second control delay

The corresponding uniform traffic flows for each leg that achieves the capacities in Figure 6.1 are shown below in Table 6.2.

Table 6.2 – Uniform traffic flows corresponding to total capacity of signalised roundabout

Cycle Time (s)	Left Turn (veh/hr)	Through Movement (veh/hr)	Right Turn (veh/hr)	Total Entry (veh/hr)
60	268	268	268	804
75	273	273	273	819
90	275	275	275	825
105	277	277	277	831

An excel table was developed to check the capacity of the LinSig model. For equal flows from all four legs of the roundabout and a 105 second phase time the standard phasing capacity to allow for no continually increasing queue and a control delay of 79 seconds is shown in Table 6.3.

Table 6.3 – Capacity values Excel for 105s phase time Semi Rural / Urban Environment

Saturation flow	1800	veh/hr			
Cycle time	105	sec			
Clearance time	2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	24.25	24.25	24.25	24.25	
Proportion of time (u)	0.23	0.23	0.23	0.23	
Q (one lane)	416	416	416	416	**1663**
Q (two lanes)	831	831	831	831	**3326**
Control Delay (s)	26	26	26	26	**79**

A level of service for a control delay of 79 seconds corresponds to approximately a LOS F, therefore this capacity best represents the total effective capacity of the signalised roundabout before reaching the LOS F requirements.

Here the average control delay per passenger car unit is approximately 80 seconds, corresponding to a LOS F. The demand flow that corresponds to this requirement is 416 vehicles per lane of entry and 831 vehicles per entry (two lanes).

We see here that the LinSig value closely resemble the Excel value, this is due to the control delay both representing approximately 80 seconds. This shows that the LinSig model represents the queue discharge values found from the field research, thus various origin and destination matrices can be applied and the capacities calculated effectively.

The governing capacity before the lanes reach 100% saturation flow and an excess of 80 second control delay is 3324 veh/hr in a semi-rural/urban environment. This represents a queue discharge headway of 1800 veh/hr.

From Table F.4 the average maximum queue length under a cycle time of 105 seconds reaches 17 passenger car units which corresponds to a total of approximately 100m in length.

The total capacity the intersection is able to produce within an hour interval is determined based on the equations stated in section 3.2.3. These capacities are smaller than the capacities governed by the control delay requirement as it does not account for the queued vehicles that have not entered into the roundabout intersection. The capacities for each cycle time that the intersection is able to produce within an hour interval are shown in Figure 6.2.

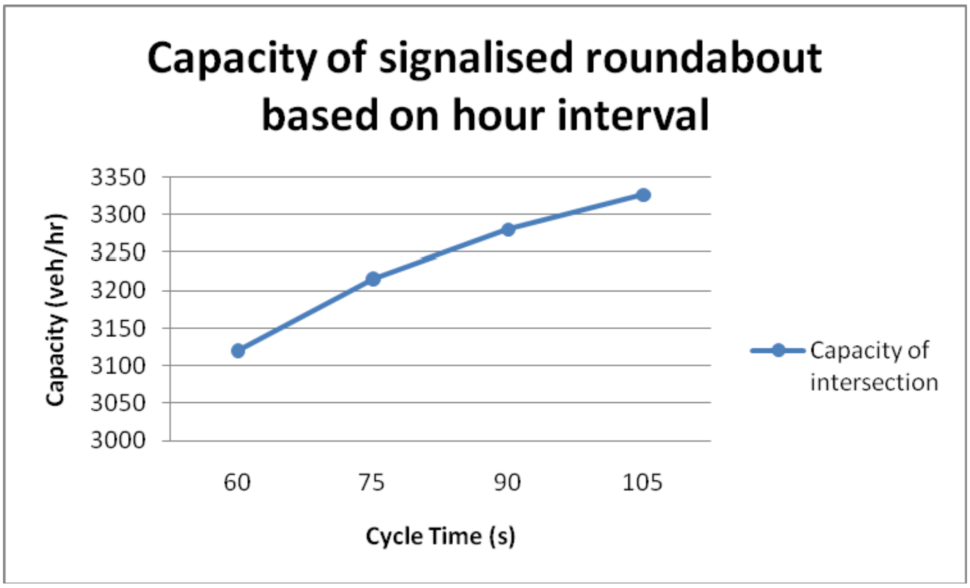


Figure 6.2 – Capacity of signalised roundabout based on hour interval

Case 2: 0 second all-red interval time

When providing a 0 second all-red interval the clearance from the following green phase will be based purely on the geometric delay provided by the roundabout. From Table 4.8 the through movement distance is 47m, however the distance to the first conflict point is approximately 35m.

From the field research it shows that from a stopped start the average cruise speed is 26.34km/hr with a maximum speed recorded of 31.8km/hr. Therefore to obtain a desirable 3 second clearance time as stated in Table 4.2 a vehicle travelling through the end of the yellow phase would be impacted upon if an entering vehicle was exceeding **42km/hr** from the start of the following green phase.

Due to this speed being greater than the maximum speed recorded from the field test it is feasible to have the following green phase start immediately after the preceding phase yellow time.

As there is no lost time due to all-red intervals, the capacity for all cycle times per lane can be worked out simply from equation 3.5 as:

$$Q = su$$

$$Q = 1800 \text{ veh/hr} \times 1$$

$$Q = 1800 \text{ veh/hr per lane of entry flow}$$

Therefore due to two lanes of flow, the capacity will be equal to **3600 veh/hr**.

When assessing the capacity based on a control delay of 80 seconds to relate it to level of service F requirements stated in Table 3.7, the optimal phase time would be a 60 second phase time according to Figure 6.1. A 60 second phase time is used as the minimum cycle time to still provide for pedestrian movements.

The results obtained from the LinSig output which can be seen from Table F.5 is that a capacity of **3708 veh/hr** is able to be achieved before an 80 second control delay is experienced by any vehicle. This would be the maximum capacity able to be achieved based on the control delay LOS F requirements.

Case 3: 3 second clearance time (-1 second all-red interval)

Due to the LinSig model unable to overlap signal timings the capacities calculated based on a 3 second clearance time will be assessed using excel and the equations represented in section 3.2.3. The results are tabulated in Table F.6 in Appendix F. Figure 6.3 shows the capacity the intersection is able to provide and the corresponding cycle time.

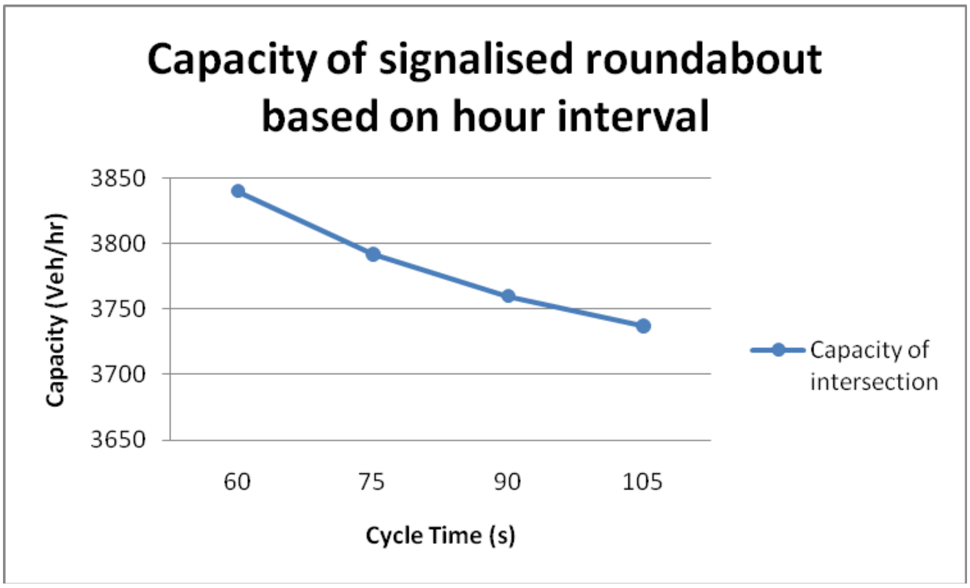


Figure 6.3 – Capacity of Signalised Roundabout with 3 second clearance time

These capacities reflect the total capacity the roundabout is able to handle within an hour interval and does not represent LOS F requirements for 80 second controlled delay. It represents the total amount of vehicles that are able to enter into the intersection within an hour interval.

6.1.1.2 Urban Environment Saturation flow 1900 veh/hr

Case 1: 2 second all-red interval

A uniform traffic flow was entered into the LinSig model to determine the capacity of the signalised roundabout. The uniform traffic flows were increased until LOS F requirements were met from Table 3.7, with control delay of up to 80 seconds and a lane saturation of 100%.

Shown in Figure 6.4 are the total capacities for the signalised intersection based on different cycle times. The data tables are attached to Appendix F in Tables F.7 to F.10.

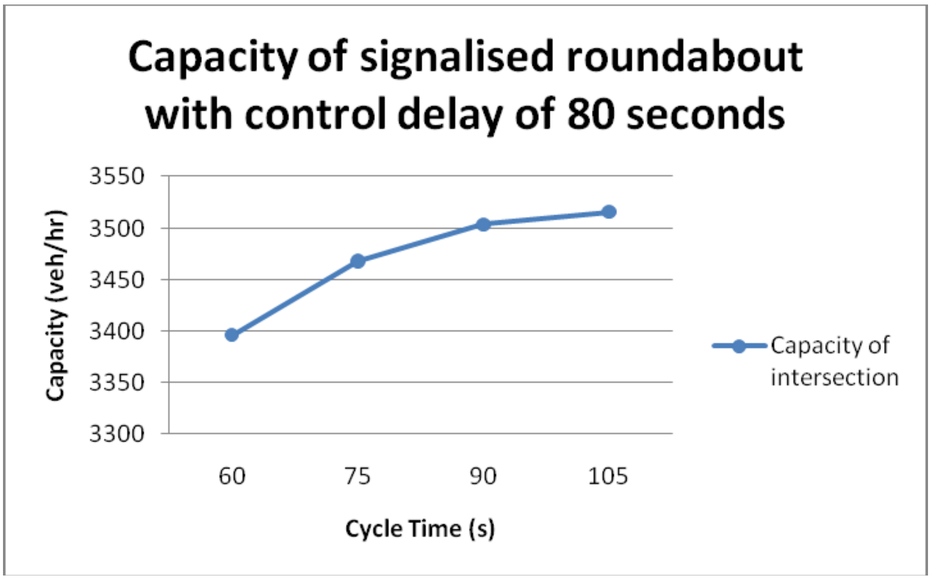


Figure 6.4 – Capacity of Signalised Roundabout with 2 second all-red interval Urban environment

The corresponding uniform traffic flows for each leg that achieved the capacities are shown below in Table 6.4.

Table 6.4 – Uniform traffic flows corresponding to total capacity of signalised roundabout

Cycle Time (s)	Left Turn (veh/hr)	Through Movement (veh/hr)	Right Turn (veh/hr)	Total Entry (veh/hr)
60	283	283	283	849
75	289	289	289	867
90	292	292	292	876
105	293	293	293	879

An excel table was developed to check the capacity of the LinSig model. For equal flows from all four legs of the roundabout and a 105 second phase time the standard phasing capacity to allow for no continually increasing queue and a control delay of 79 seconds is shown in Table 6.5.

Table 6.5 – Capacity values Excel for 105s phase time Semi-Rural / Urban Environment

Saturation flow	1800	veh/hr			
Cycle time	105	sec			
Clearance time	2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	24.25	24.25	24.25	24.25	
Proportion of time (u)	0.23	0.23	0.23	0.23	
Q (one lane)	439	439	439	439	**1755**
Q (two lanes)	878	878	878	878	**3510**
Control Delay (s)	26	26	26	26	**79**

A level of service for a control delay of 79 seconds corresponds to approximately a LOS F, therefore this capacity best represents the total effective capacity of the signalised roundabout before reaching the LOS F requirements.

Here the average control delay per passenger car unit is approximately 80 seconds, corresponding to a LOS F. The demand flow that corresponds to this requirement is 439 vehicles per lane of entry and 878 vehicles per entry (two lanes).

We see here that the LinSig value closely resemble the Excel value, this is due to the control delay both representing approximately 80 seconds. This shows that the LinSig model represents the queue discharge values found from the field research, thus various origin and destination matrices can be applied and the capacities calculated effectively.

The governing capacity before the lanes reach 100% saturation flow and an excess of 80 second control delay is 3510 veh/hr in an urban environment where the queue discharge resembles 1900 veh/hr.

From Table F.10 the average maximum queue length under a cycle time of 105 seconds reaches 18 passenger car units which corresponds to an approximate total length of 105m.

The total capacity the intersection is able to produce within an hour interval is determined based on the equations stated in section 3.2.3. These capacities are smaller than the capacities governed by the control delay requirement as it does not account for the queued vehicles that have not entered into the roundabout intersection. The capacities for each cycle time that the intersection is able to produce within an hour interval are shown in Figure 6.5.

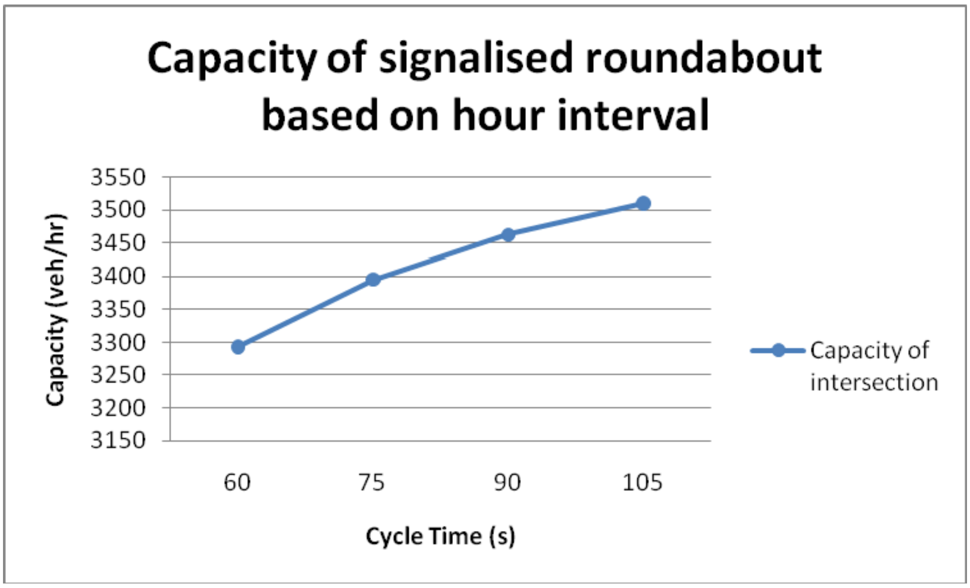


Figure 6.5 – Capacity of signalised roundabout based on hour interval

Case 2: 0 second all-red interval time

When providing a 0 second all-red interval the clearance from the following green phase will be based purely on the geometric delay provided by the roundabout. From Table 4.8 the through movement distance is 47m, however the distance to the first conflict point is approximately 35m.

From the field research it shows that from a stopped start the average cruise speed is 26.34km/h with a maximum speed recorded of 31.8km/h. Therefore to obtain a desirable 3 second clearance time as stated in Table 4.2 a vehicle travelling through the end of the yellow phase would be impacted upon if an entering vehicle was exceeding **42km/h** from the start of the following green phase.

Due to this speed being greater than the maximum speed recorded from the field test it is feasible to have the following green phase start immediately after the preceding phase yellow time.

As there is no lost time due to all-red intervals the capacity for all cycle times per lane can be worked out simply from equation 3.5 as:

Q = su

Q = 1900 veh/hr x 1

Q = 1900 veh/hr per lane of entry flow

Therefore due to two lanes of flow, the capacity will be equal to **3800 veh/hr**.

When assessing the capacity based on a control delay of 80 seconds to relate it to LOS F requirements stated in Table 3.7, the optimal phase time would be a 60 second phase time. A 60 second phase time is used as the minimum cycle time to still provide for pedestrian movements.

The results obtained from the LinSig output which can be seen from Table F.11 is that a capacity of **3935 veh/hr** is able to be achieved before an 80 second control delay is experienced by any vehicle.

Case 3: 3 second clearance time (-1 second all-red interval)

Due to the LinSig model unable to overlap signal timings the capacities calculated based on a 3 second clearance time will be assessed using Excel and the equations represented in section 3.2.3. The results are tabulated in Table F.12 in Appendix F. Figure 6.6 shows the capacity the intersection is able to provide under an urban environment and the corresponding cycle time.

These capacities reflect the total capacity the roundabout is able to handle and does not represent LOS F requirements for 80 second controlled delay. It represents the total amount of vehicles that are able to enter into the intersection within an hour interval.

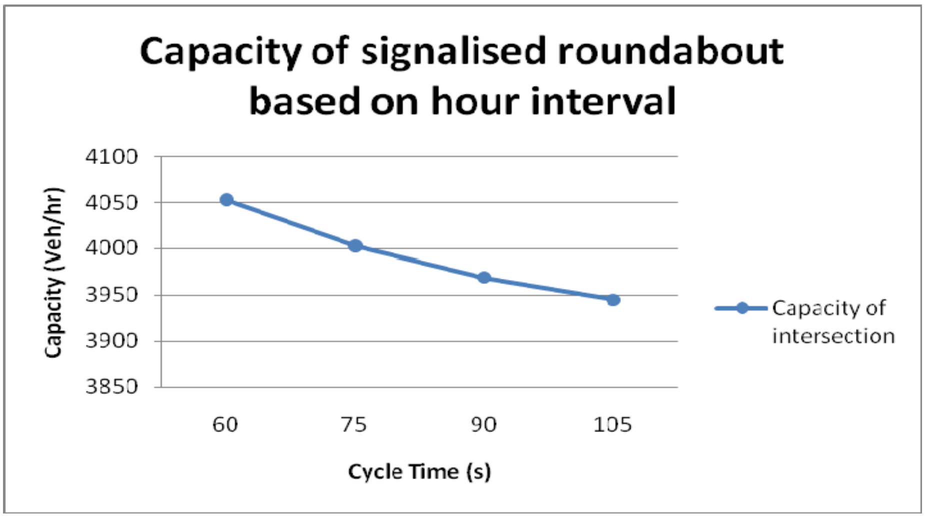


Figure 6.6 – Capacity of Signalised Roundabout with 3 second clearance time

6.1.2 UK Phasing – No pedestrian movements

The governing factor for the capacity of the intersection using the UK phasing technique is the inner lane storage length and the amount of right turn movements within the green phase period.

The 50m inscribed diameter roundabout has a potential maximum inner lane capacity of 5 passenger car units if both lanes within the circulating carriageway are full. If the demand exceeds this capacity then the excess queue will impede on the through movement of other vehicles.

Only a 60 second phase time will be analysed for the intersection due to longer phase times causing excessive queue lengths within the circulating carriageway. A 60 second phase time does not allow for pedestrian phase times, therefore will not be accounted for in the UK phasing structure.

Therefore the requirement to measure when the intersection has reached its full capacity and provides a LOS F is as follows:

- Inner lane storage demand exceeds 5 passenger car units per phase and effects opposing through movement.
- Control delay of any vehicle exceeds 80 seconds.
- Lane saturation flow exceeds 100%.

6.1.2.1 Semi-rural / Urban Environment Saturation flow 1800 veh/hr

60 Second Phase Time

When applied with a uniform traffic flow as previously done in the standard phasing results the capacity achieved is 3696 veh/hr as shown by the origin to destination volumes in Table 6.6.

Table 6.6 – Capacity values LinSig for 60s phase time Semi Rural / Urban Environment

	Destination					
Origin		A	B	C	D	Total
	A	0	308	308	308	924
	B	308	0	308	308	924
	C	308	308	0	308	924
	D	308	308	308	0	924
	Tot.	924	924	924	924	**3696**

As seen in Table G.2 in Appendix G the north, west and south inner lane ahead lanes have exceeded its 2 passenger car unit limit. The limit has been set at 14m length which is equal to 2.4 passenger car units which is why the values at 2.4 are highlighted in red. This is due to the 14m length of storage based on the Austroad (2011) design guidelines for a 50m inscribed diameter roundabout.

Due to the through lane proceeding whilst this excess queue has not had a chance to clear this will cause the intersection to fail rapidly.

The saturation flow and journey times are shown in Table G.1 in Appendix G where the longest movement from Zone B to Zone A requires a journey time of 73.87 seconds which is approaching the value of 80 seconds (LOS F) in control delay.

6.1.2.2 Urban Environment Saturation flow 1900 veh/hr

60 Second Phase Time

When applied with a uniform traffic flow as previously done in the standard phasing results the capacity achieved is 3696 veh/hr as shown in Table 6.7.

Table 6.7 – Capacity values LinSig for 60s phase time Urban Environment

	Destination					
Origin		A	B	C	D	Total
	A	0	308	308	308	924
	B	308	0	308	308	924
	C	308	308	0	308	924
	D	308	308	308	0	924
	Tot.	924	924	924	924	**3696**

This reflects the semi-rural/urban case where the intersection is subjected to a queue discharge of 1800 veh/hr. This is due to the limit of the circulating carriageway storage length as the governing factor. As the volume of traffic at 1800 veh/hr already supplies the demand for the circulating carriageway storage requirements then a queue discharge of 1900 veh/hr does not have an impact as the extra vehicles are unable to proceed through the intersection.

The impact it has which can be seen from Table G.4 in Appendix G is lower queue lengths for the entry lanes and a lower degree of saturation. Also due to the faster queue discharge headways the journey times for each vehicle are shorter which is shown in Table G.3 in Appendix G.

6.2 Signalised Roundabout 60m diameter

The results are combined into both standard phasing and UK phasing sections. For the standard phasing the results simulated that of a 50m inscribed diameter roundabout with only the impact of the U turn movements being affected due to the different circulating carriageway storage lengths.

The inner lane storage length of the 60m diameter roundabout is 11m in length which is less than the 14m storage length for the 50m inscribed diameter roundabout. Therefore due to this it has been modelled that only 2 passenger car units are able to occupy the circulating carriageway lanes for each lane.

6.2.1 Standard Phasing

Due to the rotation of the phasing going counter clockwise the diameter of the inscribed roundabout does not have an impact on the capacity that it can handle for the 0 and 2 second all-red intervals. The only impact the diameter has is for providing the desirable 3 second clearance time due to longer geometric delay for a vehicle to navigate around the roundabout and the storage length for vehicles making a U turn manoeuvre.

The storage length within the circulating carriageway is able to handle 4 passenger car units per phase. Therefore the following U turn movements in Table 6.8 are not to be exceeded for each phase time for the capacity of the 60m inscribed diameter model to allow it to differ from the 50m inscribed diameter model.

Table 6.8 – Maximum U turn movements for 60m signalised roundabout

Cycle Time (s)	All-red interval (s)	Maximum U-turn movements (veh/hr)
60	2	1108
	0	960
	-2	847
75	2	860
	0	768
	-1	729
90	2	702
	0	640
	-2	588
105	2	594
	0	549
	-2	510

Thus the 0 and 2 second all-red interval capacities calculated for the 50m inscribed diameter can be applied for the 60m inscribed diameter intersection. Therefore only the 3 second clearance value will be analysed for the 60m inscribed diameter roundabout.

Case 2: 0 second all-red interval time

When providing a 0 second all-red interval the clearance from the following green phase will be based purely on the geometric delay provided by the roundabout. From Table 4.8 the through movement distance is 63m, however the distance to the first conflict point is approximately 43m.

From the field research it shows that from a stopped start the average cruise speed is 27.91km/h with a maximum speed recorded of 30.00km/h. Therefore to obtain a desirable 3 second clearance time as stated in Table 4.2 a vehicle travelling through the end of the yellow phase would have to be exceeding **51.6km/h** to impact on a vehicle entering at the end of the yellow phase.

Due to this speed being greater than the maximum speed recorded from the field test it is feasible to not provide any all-red interval and have the following green phase start immediately after the preceding phase yellow time.

Case 3: 3 second clearance time (-2 second all-red interval)

Due to the longer geometric delay provided by the 60m inscribed diameter the following phase is able to start 2 seconds before the end of the preceding yellow phase and still provide a 3 second clearance time. The capacities have also been calculated in Excel and represent the total capacity within an hour interval that the intersection is able to account for.

These capacities reflect the total capacity the roundabout is able to handle and does not represent LOS F requirements for 80 second controlled delay. It represents the total amount of vehicles that are able to pass through the intersection within an hour interval.

Figure 6.7 represents the semi-rural/urban environment where a queue discharge of 1800 veh/hr is experienced. The tabulated values are shown in Table F.13 attached in Appendix F.

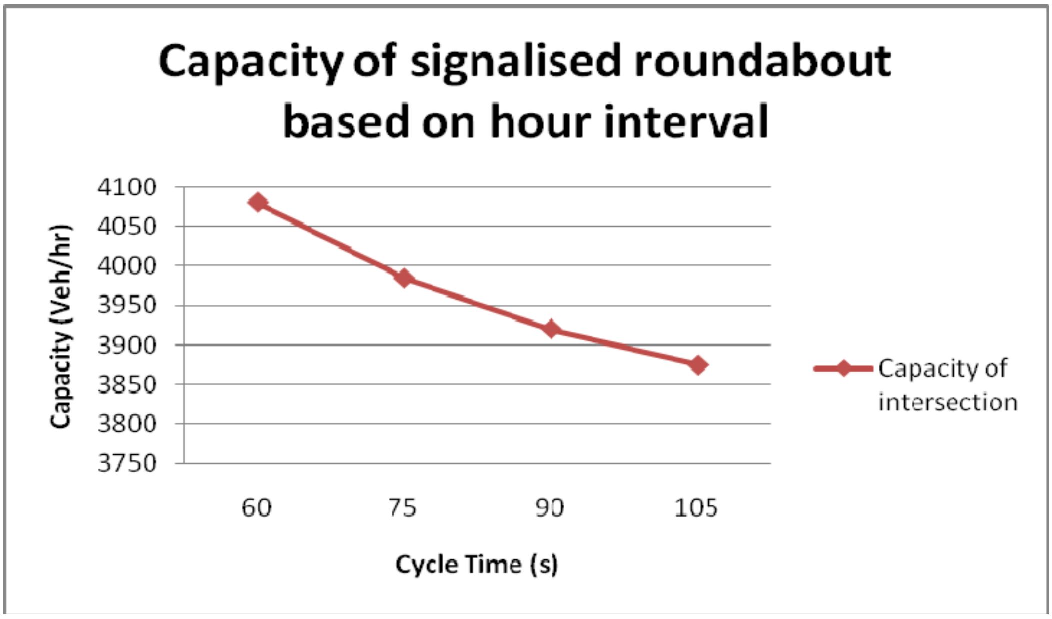


Figure 6.7 – Capacity of Signalised Roundabout with 3 second clearance time Semi-rural / Urban environment

Figure 6.8 represents an urban environment where a queue discharge of 1900 veh/hr is experienced. The tabulated values are shown in Table F.14 attached in Appendix F.

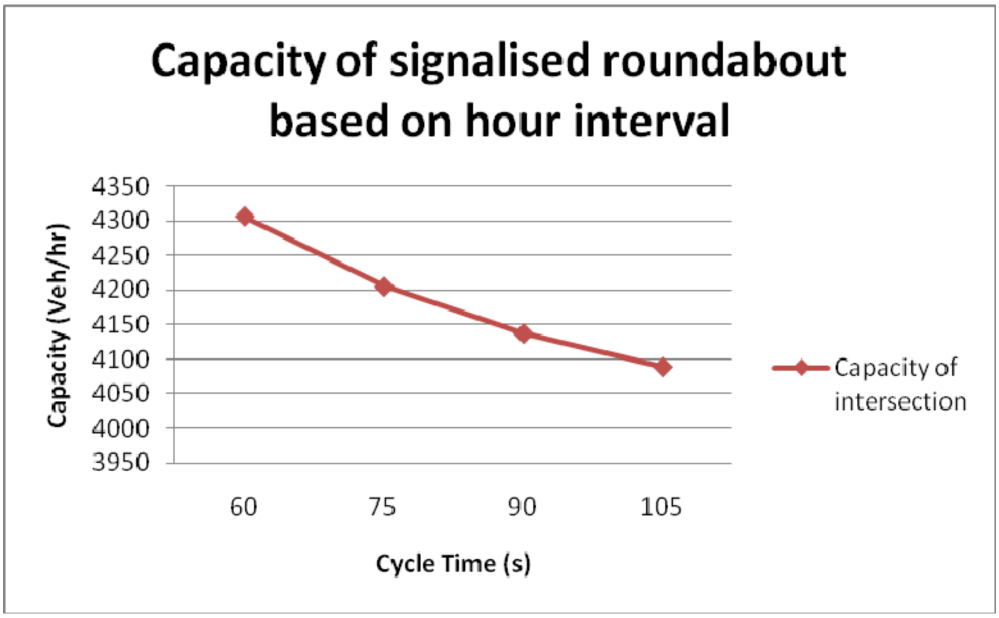


Figure 6.8 – Capacity of Signalised Roundabout with 3 second clearance time Urban environment

6.2.2 UK Phasing – No pedestrian movements

The governing factor for the capacity of the intersection using the UK phasing technique is the inner lane storage length and the amount of right turn movements within the green phase period.

The 60m inscribed diameter roundabout has a potential maximum inner lane capacity of 4 passenger car units if both lanes within the circulating carriageway are full. If the demand exceeds this capacity then the excess queue will impede on the through movement of other vehicles.

Only a 60 second phase time will be analysed for the intersection due to longer phase times causing excessive queue lengths within the circulating carriageway. A 60 second phase time does not allow for pedestrian phase times, therefore will not be accounted for in the UK phasing structure.

Therefore the requirement to measure when the intersection has reached its full capacity and provides a LOS F is as follows:

- Inner lane storage demand exceeds 4 passenger car units per phase and effects opposing through movement.
- Control delay of any vehicle exceeds 80 seconds.
- Lane saturation flow exceeds 100%.

6.2.2.1 Semi-rural / Urban Environment Saturation flow 1800 veh/hr

60 Second Phase Time

When applied with a uniform traffic flow as previously done in the standard phasing results the capacity achieved is 2940 veh/hr as shown in the origin to destination traffic volumes in Table 6.9.

Table 6.9 – Capacity values LinSig for 60s phase time Semi Rural / Urban Environment

	Destination					
		A	B	C	D	Total
Origin	A	0	245	245	245	735
	B	245	0	245	245	735
	C	245	245	0	245	735
	D	245	245	245	0	735
	Tot.	735	735	735	735	**2940**

As seen in Table H.2 in Appendix H all the inner right turn ahead lanes have exceeded its 2 passenger car unit limit. The limit has been set at 11.5m length which is equal to 2.0 passenger car units which is why the values at 2.0 or above are highlighted in red. This is due to the 11.5m length of storage based on the Austroad (2011) design guidelines for a 60m inscribed diameter roundabout.

Due to the through lane proceeding whilst this excess queue has not had a chance to clear this will cause the intersection to fail rapidly.

The saturation flow and journey times are shown in Table H.1 in Appendix H where the movement from Zone D to Zone C requires a journey time of 62.11 seconds which is not relatively close to reaching the value of 80 seconds (LOS F) in control delay. The control delay requirement is not met before the excess queuing of the inner lane storage.

6.2.2.2 Urban Environment Saturation flow 1900 veh/hr

60 Second Phase Time

When applied with a uniform traffic flow as previously done in the standard phasing results the capacity achieved is 2940 veh/hr as shown in the origin to destination traffic volumes in Table 6.10.

Table 6.10 – Capacity values LinSig for 60s phase time Urban Environment

	Destination					
		A	B	C	D	Total
Origin	A	0	245	245	245	735
	B	245	0	245	245	735
	C	245	245	0	245	735
	D	245	245	245	0	735
	Tot.	735	735	735	735	**2940**

This reflects the semi-rural/urban case where the intersection is subjected to a queue discharge of 1800 veh/hr. This is due to the limit of the circulating carriageway storage length as the governing factor. As the volume of traffic at 1800 veh/hr already supplies the demand for the circulating carriageway storage requirements then a queue discharge of 1900 veh/hr does not have an impact as the extra vehicles are unable to proceed through the intersection.

The impact it has which can be seen from Table H.4 in Appendix H is lower queue lengths for the entry lanes and a lower degree of saturation. Also due to the faster queue discharge headways the journey times for each vehicle is shorter which is shown in Table H.3 in Appendix H compared to that of Table H.1.

7. CAPACITY OF SIGNALISED ROUNDABOUTS

Due to the variability of phasing techniques, roundabout geometry and traffic flow characteristics there are numerous impacts these factors can have on the capacity of a signalised roundabout. This section will discuss these factors based on the determined results stated in the previous section.

7.1 Effects of inscribed diameter

The effects of the inscribed diameter had different impacts to the capacity depending upon the phasing technique used. For the standard phasing technique the effect of the inscribed diameter was minimal towards the capacity, only affecting the geometric delay and red clearance times. For the UK phasing the inscribed diameter affected the capacity significantly due to the amount of inner lane capacity it was able to provide.

This is discussed in detail in the following sections.

7.1.1 Standard Phasing

Shown in Figure 7.1 are the capacities for both 50m and 60m inscribed diameters based on the 0 second all-red interval time between phases. These capacities reflect the total entry capacity within an hour interval for the signalised roundabout intersections.

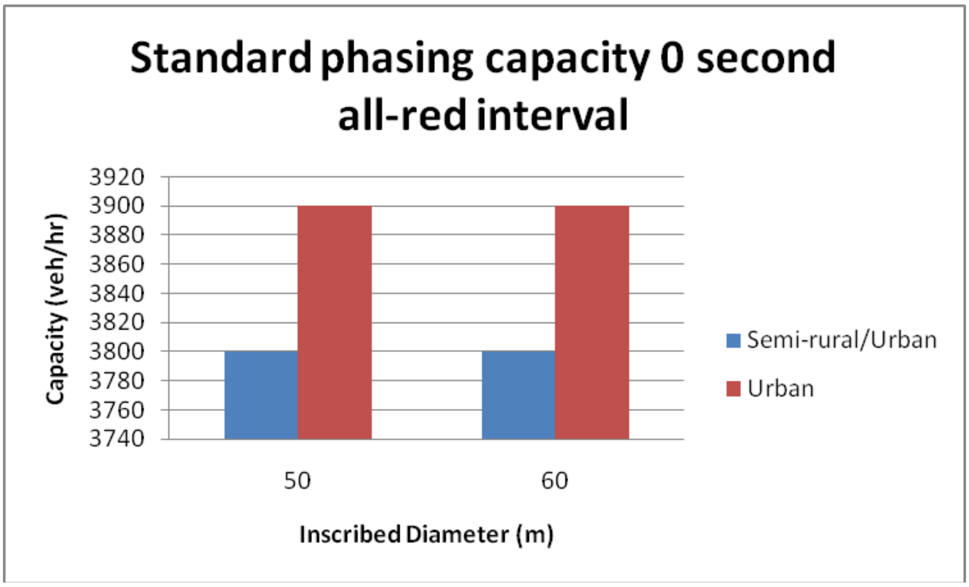


Figure 7.1 – Capacity for signalised roundabout for different inscribed diameters

From Figure 7.1 it can be seen that the inscribed diameter has no impact on the capacity when applied with a 0 second all-red interval. This also applies to any all-red interval time above 0 seconds, noting that two constraints are met:

- U turn movements are not to exceed the inner lane storage capacity for any green phase period
- A maximum cycle phase of 105 seconds is to be used so vehicles aren't exposed to a control delay greater than 80 seconds.

The reasoning behind this is that the phasing technique only allows one leg to enter the roundabout during a green phase period, therefore the geometry of the roundabout does not have an effect on the entering capacity of the roundabout.

The inscribed diameter does not have an impact on the capacity of the roundabout directly, however due to the larger inscribed diameter there is potential to start the following green phase earlier due to the larger geometric delay provided by the geometry of the roundabout.

Taking both the 50m and 60m examples and looking at saturated conditions where an entering vehicle will be taking off from a stopped start. Table 7.1 shows the excess clearance time available when providing for a desirable 3 second clearance time from an entering vehicle. The speed of the entering vehicle will be taken as an average acceleration speed of 30km/h, based on the field research conducted on the geometric delay at roundabouts.

Table 7.1 – Excess clearance time at 30km/h entering vehicle speed

Inscribed diameter (m)	Distance to conflict point (m)	Excess clearance distance after 3 seconds (m)	Excess clearance time after 3 seconds (s)
50	35	10	1.2
60	43	18	2.16

The conditions stated in Table 7.1 have been modelled in the results section for both 50m and 60m inscribed diameter lengths. The results showed that in both semi-rural/urban and urban environments the 60m inscribed diameter allowed greater entry capacities due to the longer clearance time it could provide between phases due to its larger clearance distance. Figures 7.2 and 7.3 shows the comparison of capacities between both models.

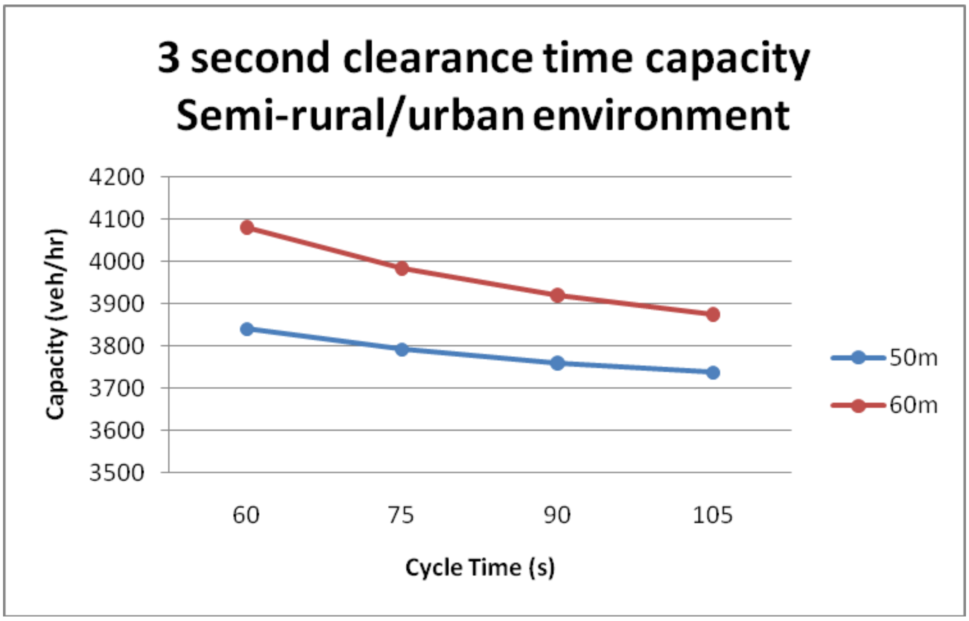


Figure 7.2 – Capacity for signalised roundabout for different inscribed diameters

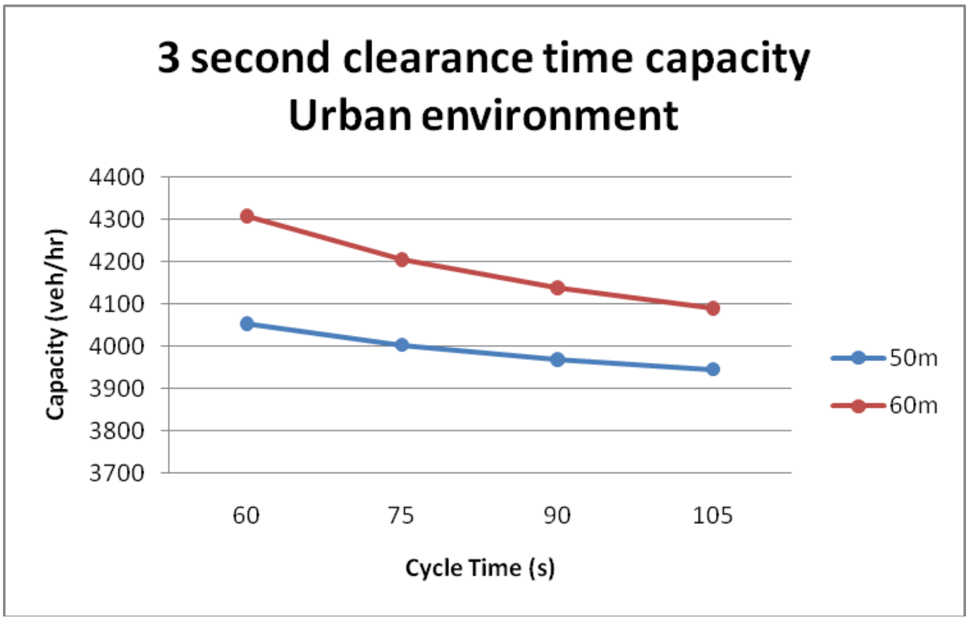


Figure 7.3 – Capacity for signalised roundabout for different inscribed diameters

For both environments it is clear that the 60m inscribed diameter model provides a larger entry capacity. The difference in capacity is reduced depending on the cycle time as the larger cycle time reduces the frequency of the phase changes. The larger cycle times do not allow the following phase to utilise a segment of the roundabout as often as a smaller cycle time, thus reducing entering capacities.

7.1.2 UK Phasing – No pedestrian movements

The effect the inscribed diameter had on the UK phasing structure significantly impacted on the capacity of the intersection. Shown in Figure 7.4 is the difference in capacities the intersection was able to handle during a 60 second cycle time.

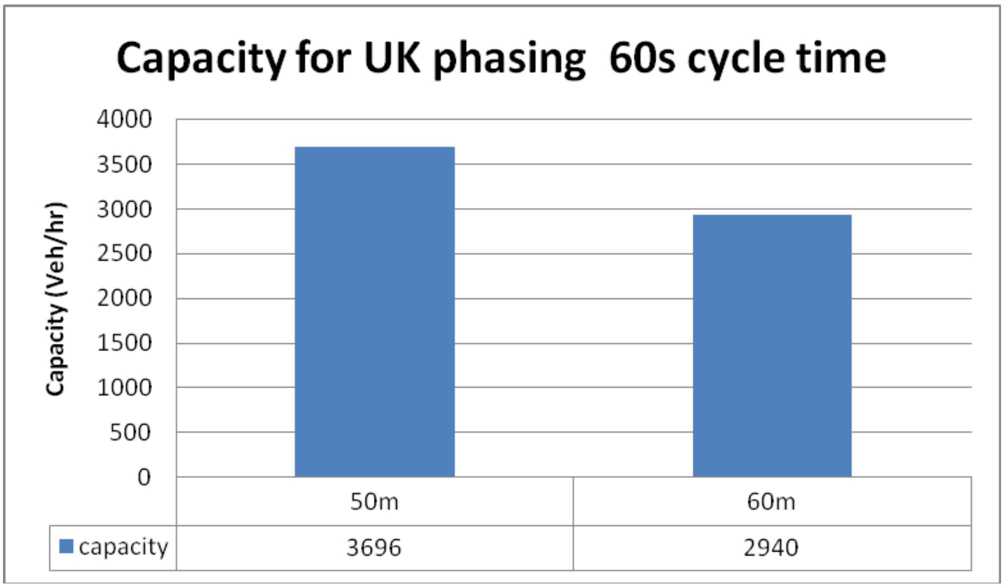


Figure 7.4 – Capacity for signalised roundabout for different inscribed diameters UK phasing

The main difference that affects the capacity of the roundabout is the inner lane storage capacity. The 50m inscribed diameter model was modelled on the basis of being able to store up to 5 passenger car units within the inner lane storage lanes and the 60m inscribed diameter model only being able to store 4 passenger car units.

It was expected the larger diameter roundabout would be able to hold a larger inner lane capacity, however based on Austroads (2011) standards, the perpendicular symmetry and the entry and exit curves applied, this was not the case. Due to the variability in geometry that can be applied to a roundabout intersection, the capacities will be based on inner lane storage capacities and it will be assumed that generally larger diameter roundabouts will be able to hold a larger inner lane capacity within its circulating carriageway.

The inscribed diameter for the UK phasing technique can greatly improve the capacity of the intersection if it increases the inner lane storage capacities. The traffic volumes and their origin and destination flows have to be thoroughly assessed to insure that the inner lane storage capacities are not to be over saturated, as this has a detrimental effect to the performance of the intersection. From Figure 7.4 if the inner lane capacities drop from 5 passenger car units to 4 it has an impact of approximately 700 veh/hr due to the over saturation of the inner lanes.

Generally this phasing technique would only be considered on large roundabouts with substantial inner lane capacities. It is also beneficial if this was aided with low right turn movements and heavy through and left turn movements.

7.2 Effects of queue discharge headway

The effects of the queue discharge headway was assessed after finding that in different environments, traffic flows would have different queue discharges at signalised intersections. In a semi-rural/urban environment the queue discharge of approximately 1800 veh/hr was observed, where in a more urban environment a queue discharge of approximately 1900 veh/hr was observed.

7.2.1 Standard Phasing

The queue discharge headway has a significant impact on the standard phasing technique as it directly reflects the equation 3.5 of Q = su. Figure 7.5 shows the difference in capacities for both the different queue discharges using the 2 second all-red interval phasing structure.

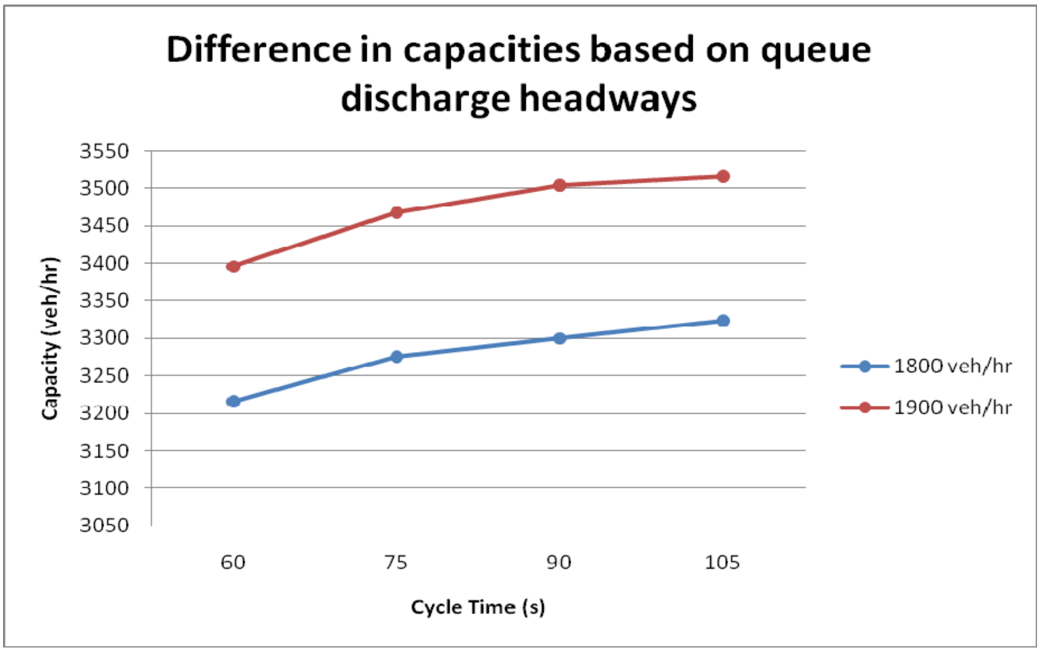


Figure 7.5 – Difference in capacities based on queue discharge headways

This shows that there is approximately an extra 180 to 200 veh/hr travelling through the intersection when the queue discharge is 1900 veh/hr instead of 1800 veh/hr. This corresponds to the extra 200 veh/hr that is able to travel through the intersection when there is no all-red interval applied between phasing.

Therefore the impact the queue discharge has on the signalised intersection using the standard phasing technique directly reflects equation 3.5. The increased capacity reflects the increased queue discharge flow travelling through the total effective green time.

7.2.2 UK Phasing – No pedestrian movements

The two variable queue discharge headways of 1800 veh/hr and 1900 veh/hr had no impact on the capacity of the intersection. This was due to the capacity of the inner lanes being over saturated, therefore the higher queue discharge of 1900 veh/hr was not utilised as the demand for the capacities were being achieved at 1800 veh/hr.

Along with this, due to the small capacities of 4 and 5 passenger car units over two lanes, both queue discharge rates were able to empty the inner lanes within their allocated green phase period.

These two situations determined that for the UK phasing in roundabouts up to 60m, the effect of the queue discharge headway times has no impact on the capacities for a 60 second cycle time with uniform flow.

7.3 Effects of cycle times

The cycle times can have a major impact on allowing vehicles to enter the intersection in an effective manner. A long cycle time may cause vehicles to experience excessive delay times and a short cycle time might lose effective green times for vehicles to travel through the intersection. The impacts the cycle times had on the capacities of the signalised roundabout intersections are discussed in the following sections.

7.3.1 Standard Phasing

The cycle times impacted on the capacity proportionally to the variable all-red interval times and red clearance times between each phase. When an all-red interval time of 2 seconds was used in the standard phasing cycle, it requires that for a 2 second period no vehicles could enter into the intersection. When this was used in parallel with a short cycle time, it increased the total time of vehicles unable to enter the intersection during the hour interval, thus reducing its capacity.

Conversely when a 3 second clearance time was used, allowing the following phase to proceed before the end of the preceding phase, the short cycle time increased capacities as for a short period of time it allowed two legs of traffic to enter the intersection. The short cycle time increased the time period this situation was able to take place, thus increasing the entering capacity of the signalised roundabout intersection.

Shown below in Figure 7.6 is an example of the two situations described above corresponding to different cycle times. The example is taken from the 60m inscribed diameter roundabout in an urban environment.

It has been determined that for the 2 second all-red interval phasing technique the increase in cycle time increases the capacity from 3396 veh/hr at a 60 second cycle time to 3516 veh/hr for a 105 second cycle time. This is inversely related when providing a 3 second clearance time that allows the following phase to proceed 2 seconds before the end of the preceding phase as shown in the red line. Here we can see that the capacity of 4307 veh/hr at a 60 second cycle time is reduced to 4090 veh/hr at a 105 second cycle time.

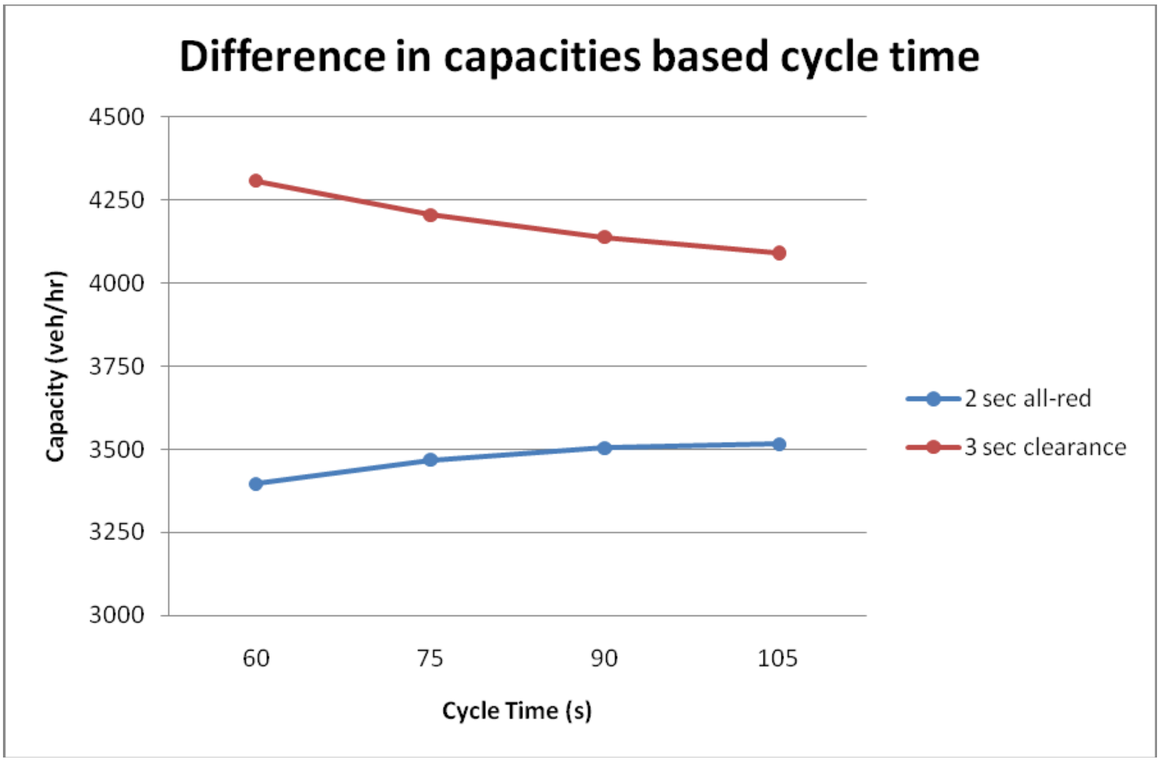


Figure 7.6 – Difference in capacities based on queue discharge headways

For the 60 second cycle time there is a difference of 911 veh/hr that are able to enter the intersection within the hour interval. This is a significant impact on the overall capacity of the roundabout. It would be at the authorities' discretion as too what clearance time and all-red intervals they would be willing to accept so that safety is not compromised.

7.3.2 UK Phasing – No pedestrian movements

Only a 60 second cycle time was assessed for this phasing structure thus no comparisons can be made. The cycle time does greatly impact on this phasing technique as it requires short cycle times to continually clear out the circulating carriageway.

For this reason only a 60 second cycle time was modelled as the uniform traffic flows applied required short phase times to clear out the inner lanes of the intersection. The impact of cycle times for this phasing technique has to be further researched but from initial findings it is found that the phase times need to reflect the demand of the traffic in regards to their origin to destination flows.

7.4 Comparison to un-signalised roundabouts

The two techniques used by both the HCM (2010) and Tan (2001) will be used to compare the calculated capacities of the signalised roundabout intersections to a corresponding un-signalised case.

The HCM (2010) capacities are tabulated in Table I.1 showing the total capacity from a uniform flow for a variable circulating flow. Looking at saturated conditions the capacities highlighted in blue are the most likely to represent the actual capacities due to an expected high circulating flow.

The capacities based on the Tan (2001) formulae are tabulated in Tables I.2 and I.3. The values of the coefficients chosen are shown in Table 7.2 below. The coefficient of α was taken as 0.1 to represent both the 50m and 60m inscribed diameter cases due to the distance of L_{ba} being between 21m and 28m for both diameters. From Figure 3.4 it can be seen that the coefficient α does not change within the L_{ba} interval of 21m to 28m.

Table 7.2 – Coefficient values used for un-signalised roundabout capacities using Tan (2001) formulae

Coefficients	Value
F	1500
f	8/9
κ	1.5
β	0.8
α	0.1

The capacities for the signalised roundabout intersections will be based on the total entry capacity of the intersection within an hour interval period.

7.4.1 Standard Phasing

The standard phasing capacities for both 50m and 60m inscribed diameters for the variable all-red intervals are shown in Table 7.3.

Table 7.3 – Capacities based on entry capacity for an hour interval

SEMI-RURAL / URBAN ENVIRONMENT

50m Inscribed Diameter Capacities (veh/hr)				
	Cycle Times (s)			
all red-interval (s)	60	75	90	105
2	3120	3216	3280	3326
0	3600	3600	3600	3600
-1	3840	3792	3760	3737

60m Inscribed Diameter Capacities (veh/hr)				
	Cycle Times (s)			
all red-interval (s)	60	75	90	105
2	3120	3216	3280	3326
0	3600	3600	3600	3600
-2	4080	3984	3920	3874

URBAN ENVIRONMENT

50m Inscribed Diameter Capacities (veh/hr)				
	Cycle Times (s)			
all red-interval (s)	60	75	90	105
2	3293	3395	3462	3510
0	3800	3800	3800	3800
-1	4053	4003	3969	3945

60m Inscribed Diameter Capacities (veh/hr)				
	Cycle Times (s)			
all red-interval (s)	60	75	90	105
2	3293	3395	3462	3510
0	3800	3800	3800	3800
-2	4307	4205	4138	4090

The HCM (2010) and Tan (2001) methods for un-signalised roundabouts calculated the capacity under a uniform flow to be approximately 4100 veh/hr. In order to achieve this capacity, the 3 second clearance method (-2 and -1 second all-red intervals) would have to be implemented. It would appear that using this technique located in an urban environment complemented with a short cycle time would improve capacities through the intersection.

As this standard phasing technique is unaffected by the percentage of right turn movements the signalised roundabout is a much better option when the right turn movements make up 40% or more of the total movements. This can be seen by the tabulated capacity results from Table I.3.

The signalised roundabout intersection is also able to cater for pedestrians and cyclists running parallel with the corresponding green time movement for vehicles, where the un-signalised case does not cater for these movements.

7.4.2 UK Phasing – No pedestrian movements

The UK phasing technique for a 60 second cycle time is only able to provide up to approximately 3700 veh/hr when the inner lane storage capacity is equal to 5 passenger car units. After this the traffic volumes cause the inner lane capacities to overflow and block the through movents, thus rapidly causing the intersection to fail.

This is still 400 veh/hr less than the expected volumes an un-signalised roundabout is able to cater for, thus making the phasing technique not effective in improving capacities. The main criteria that effects an un-signalised roundabout is the percentage of right turn movements. This is also the case for the UK phasing structure therefore along with variable traffic flows the UK phasing technique would still not be able to increase capacities for the intersection.

Due to the high risk of traffic volumes causing the circulating carriageway to experience saturated conditions and overflow of storage capacities, it would not be recommended to replace an un-signalised roundabout intersection with this phasing technique. This also is the case if high percentages of heavy vehicles are expected to navigate through the intersection.

8. RECOMMENDATIONS

It is recommended that on provision of the safety requirements from the governing authority that a red clearance time of 3 seconds be adopted to utilise the roundabouts geometry to benefit the traffic volume capacities through the intersection.

If adopting a 3 second red clearance time it is also recommended to adopt a small cycle time to utilise the roundabouts geometry and increase capacities. However the cycle time should still be long enough to provide pedestrians the required time to walk to the central median under their corresponding green phase.

The standard phasing technique is to be used over the UK phasing technique due to the following factors:

- Lower risk of capacity failing due to overflowing inner lane storage capacities
- The intersection provides for pedestrians
- The phasing technique is simpler and more effective
- The phasing technique can cater for a greater variety of origin to destination flow patterns.

Retro-fitting an un-signalised roundabout that is failing to provide for capacities is a cost effective solution in improving capacities particularly under the following conditions:

- High demand of right turn movements throughout the intersection
- High demand of pedestrian and cyclist movements.

A signalised roundabout is even more effective in improving capacities in an environment that experiences high queue discharge flows at signalised intersections. Therefore if an un-signalised roundabout is failing to cater for capacities in an urban environment, it would be recommended in retro-fitting the roundabout with signals to improve the capacities for the intersection.

9. AREAS OF FURTHER RESEARCH

Further areas of research are required to determine how the capacity is affected when the traffic volumes are applied non-uniformly. Under this research it appears that using the standard phasing technique the capacity will not change greatly with variable traffic flow demands. However, the UK phasing is predicted to improve its capacity when subjected to a greater through and left turn movement than right turn movements.

The research provided here does not assess the impact of heavy vehicle movements within the intersections. All capacities are based on passenger car units. An appropriate factor relating to passenger car units would have to be applied in parallel with the percentage of heavy vehicles as to the time required for the heavy vehicle to accelerate through the intersection.

Another factor is to analyse the impact that grades can have on the queue discharge headways for vehicles and how this affects the capacities through the intersection. It is assumed an increase in grade for accelerating vehicles will cause lower queue discharge headway flows and in turn reduce the capacity of the intersection.

When providing a comparison to the un-signalised case it would be beneficial to film a roundabout intersection working at saturated flows and determine the capacity of the roundabout and how it reflects the studies from the HCM (2010) and Tan (2001). This would give the best indication as it would better incorporate driver behaviour characteristics.

10. CONCLUSIONS

The report identified that the inscribed diameter does have an impact on the signalised roundabout intersection. For the standard phasing technique the impact the inscribed diameter had was when a 3 second clearance time was applied between phases. The increase in diameter size allowed the following phase to proceed before the end of the preceding yellow phase. The length was directly related by the amount of geometric delay the increase in diameter was able to achieve. This impacted on capacities by increasing the entry capacity for the intersection.

The increase in diameter also impacts on the inner lane storage capacities. This has a major impact on the capacities for the UK phasing technique with the increase in inner lane storage capacity greatly increasing the intersections total capacity. This factor is not as important for the standard phasing technique unless significantly high U turn movements are expected.

Queue discharge headways have a large impact on the standard phasing technique but not on the UK phasing technique. It was found that the lower queue discharge headway flows were still able to provide enough traffic volume to fill the inner lane storage requirements for the UK phasing techniques. A queue discharge flow of 1900 veh/hr compared to 1800 veh/hr was found to improve capacities by approximately 200 veh/hr for the standard phasing technique.

The cycle time has an impact on the intersections capacity depending upon the time between phase changes. If an all-red interval time of greater than 0 seconds is required for the standard phasing technique than it is better to provide a longer cycle time. If it is not required than a shorter cycle time is recommended to improve capacities. A short cycle time is recommended for the UK phasing technique to clear the circulating carriageway and keep it from overflowing.

This report has found that a signalised roundabout using the standard phasing technique is a viable option to replace an existing un-signalised roundabout that is failing to cater for capacities. This is compounded if the intersection has a high percentage of right turn movements, pedestrian flows and is located in an urban environment. The installation of signals to a roundabout is deemed to be a cost effective solution in improving capacities.

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APPENDIX A – PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 8411/8412 Research Project

PROJECT SPECIFICATION

FOR:	JARROD TAYLOR
TOPIC:	EVALUATION OF THE CAPACITY OF SIGNALISED TWO LANE ROUNDABOUTS.
SUPERVISORS:	Dr. Soma Somasundaraswaran Mr. Raymond Stafford
ENROLMENT:	ENG 4111 – S1, D, 2012; ENG 4112 – S2, D, 2012
PROJECT AIM:	This project is to investigate the maximum amount of traffic flow that a two lane signalised roundabout can sustain until one leg fails. This will be tested on various similar roundabouts operating with a specific phasing design (one leg will operate in one phase).
SPONSORSHIP:	Roads and Maritime Services.

PROGRAMME: **Issue D, 21st March 2012**

1. A complete review of local and overseas researches on traffic flow characteristics at un-signalised and signalised roundabouts.

2. Develop traffic capacity models with various radii and lane width using LINSIG, which is a computer software programme that assesses the design of signalised roundabouts and intersections.

3. Apply traffic flows to each leg of the intersection and assess the impact of traffic flows on queue lengths and level of service.

4. Establish relationships between design parameters (radius, lane widths, headway distribution e.t.c)and the capacity of a signalised roundabout.

5. Compare the traffic flow capacity of signalised roundabouts to conventional un-signalised roundabout designs.

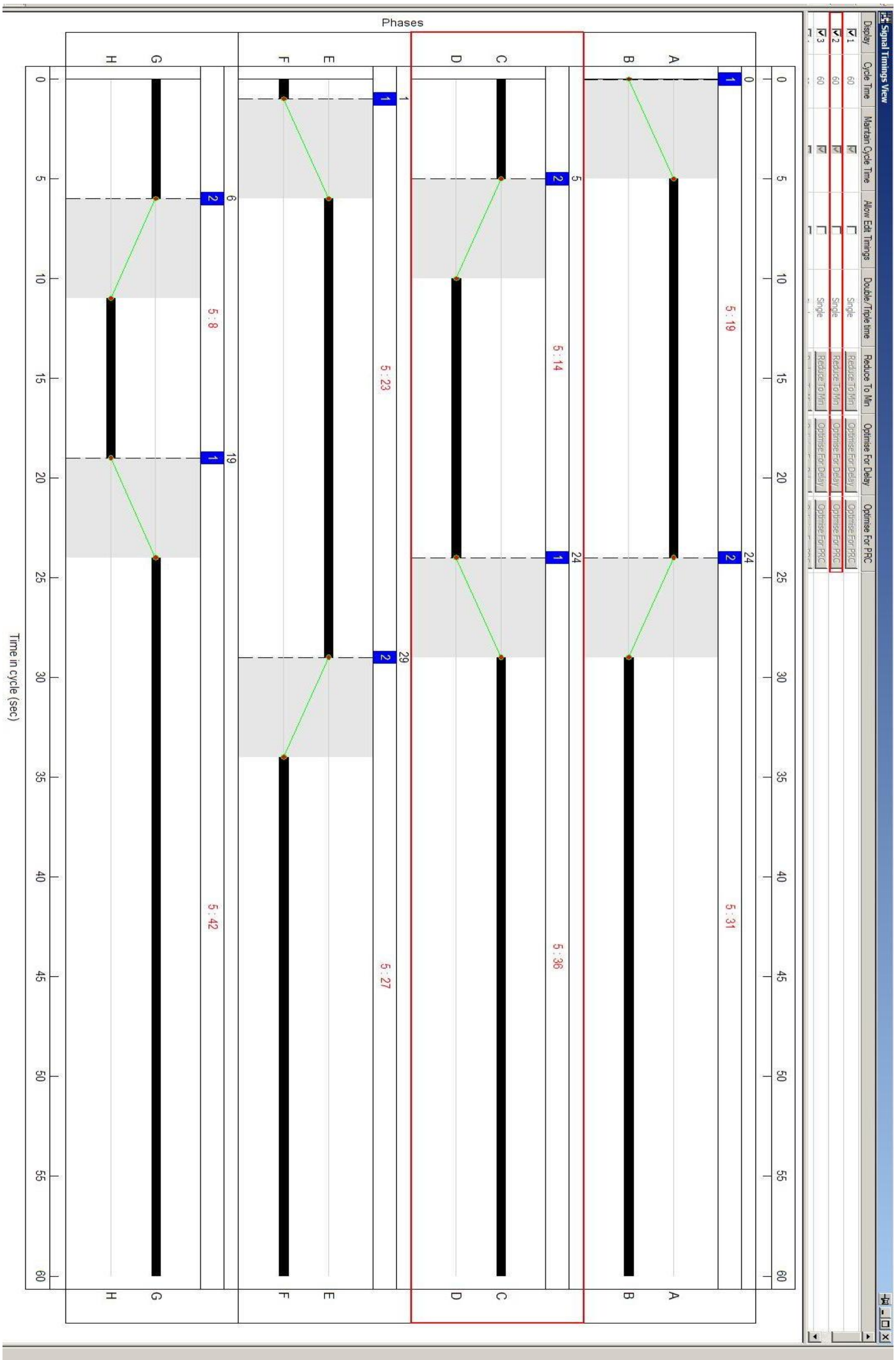
As time permits

6. Conduct field tests on vehicle gap acceptance at roundabouts and headway distribution through traffic signal phases. Use this to compare the review of local and overseas research completed in stage 1.

AGREED:

______________ (Student)	APPROVED (Supervisor)
(Jarrod Taylor)	(Soma Somasundaraswaran)
20 / 10 / 2012	21 / 03 / 2012

APPENDIX B – SAMPLE OF SIGNAL TIMINGS



APPENDIX C – DATA SHEETS FROM FIELD TESTS

Data counts for 52m inscribed diameter roundabout at Wickham.

Right Turn Movement for 52m inscribed diameter roundabout

Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Large Car	11.3	0	83	26.4
2	Large Car	12.2	0	83	24.5
3	Large Car	12.6	0	83	23.7
4	Medium Car	10.8	0	83	27.7
5	Large Car	10.1	0	83	29.6
6	Small Car	11.2	0	83	26.7
7	Large Car	11.2	0	83	26.7
8	Large Car	10.5	0	83	28.5
9	Large Car	11.8	0	83	25.3
10	Large Car	11.6	0	83	25.8
11	Large Car	12.8	0	83	23.3
12	Medium Car	11.9	0	83	25.1
13	Large Car	13.2	0	83	22.6
14	Small Car	11.1	0	83	26.9
15	Medium Car	11.8	0	83	25.3
16	Medium Car	11.5	0	83	26.0
17	Small Car	12.0	0	83	24.9
18	Large Car	12.5	0	83	23.9
19	Large Car	12.4	0	83	24.1
20	Small Car	11.2	0	83	26.7

Through Movement for 52m inscribed diameter roundabout

Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Small Car	7.2	0	53	26.5
2	Small Car	7.7	0	53	24.8
3	Medium Car	7.6	0	53	25.1
4	Large Car	7.4	0	53	25.8
5	Large Car	7.9	0	53	24.2
6	Small Car	7.4	0	53	25.8
7	Medium Car	7.6	0	53	25.1
8	Small Car	6.2	0	53	30.8
9	Medium Car	6	0	53	31.8
10	Large Car	7.4	0	53	25.8

11	Small Car	6.5	0	53	29.4
12	Medium Car	7.3	0	53	26.1
13	Large Car	7.4	0	53	25.8
14	Large Car	7.1	0	53	26.9
15	Large Car	7.1	0	53	26.9
16	Medium Car	7.3	0	53	26.1
17	Small Car	6.9	0	53	27.7
18	Small Car	7.1	0	53	26.9
19	Large Car	7.3	0	53	26.1
20	Large Car	7.6	0	53	25.1

Left Turn Movement for 52m inscribed diameter roundabout

Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Large Car	3.4	0	12	12.7
2	Large Car	3.2	0	12	13.5
3	Small Car	3.0	0	12	14.4
4	Large Car	3.4	0	12	12.7
5	Large Car	3.3	0	12	13.1
6	Medium Car	3.5	0	12	12.3
7	Medium Car	3.2	0	12	13.5
8	Large Car	3.6	0	12	12.0
9	Large Car	3.0	0	12	14.4
10	Large Car	3.2	0	12	13.5
11	Small Car	3.1	0	12	13.9
12	Large Car	3.5	0	12	12.3
13	Medium Car	3.2	0	12	13.5
14	Small Car	3.3	0	12	13.1
15	Small Car	3.3	0	12	13.1
16	Large Car	3.5	0	12	12.3
17	Large Car	3.2	0	12	13.5
18	Large Car	3.4	0	12	12.7
19	Medium Car	3.4	0	12	12.7
20	Large Car	3.5	0	12	12.3

Right Turn Movement for 63m inscribed diameter roundabout

Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Large Car	14.6	0	102	25.15
2	Large Car	13.4	0	102	27.40
3	Large Car	13.5	0	102	27.20
4	Medium Car	12.3	0	102	29.85
5	Large Car	13.1	0	102	28.03
6	Large Car	17.8	0	102	20.63
7	Large Car	16.4	0	102	22.39
8	Large Car	14.5	0	102	25.32
9	Small Car	12.8	0	102	28.69
10	Small Car	13.7	0	102	26.80
11	Large Car	13.2	0	102	27.82
12	Large Car	15.1	0	102	24.32
13	Large Car	14.7	0	102	24.98
14	Large Car	14.3	0	102	25.68
15	Large Car	16.1	0	102	22.81
16	Medium Car	15.0	0	102	24.48
17	Large Car	13.8	0	102	26.61
18	Small Car	13.3	0	102	27.61
19	Large Car	14.1	0	102	26.04
20	Large Car	15.3	0	102	24.00

Through Movement for 63m inscribed diameter roundabout

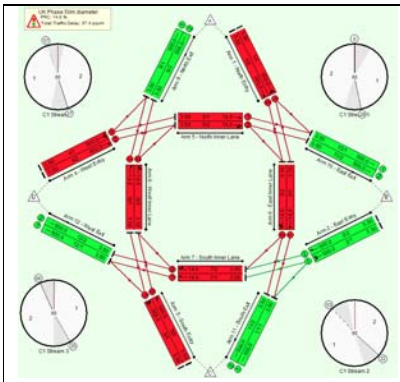
Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Large Car	7.9	0	60	27.34
2	Large Car	9.1	0	60	23.74
3	Medium Car	7.6	0	60	28.42
4	Medium Car	7.5	0	60	28.80
5	Large Car	7.8	0	60	27.69
6	Small Car	7.8	0	60	27.69
7	Large Car	7.2	0	60	30.00
8	Large Car	7.5	0	60	28.80
9	Small Car	7.4	0	60	29.19
10	Medium Car	7.8	0	60	27.69
11	Large Car	8.2	0	60	26.34
12	Medium Car	7.6	0	60	28.42
13	Large Car	7.9	0	60	27.34
14	Small Car	7.4	0	60	29.19

15	Medium Car	7.7	0	60	28.05
16	Large Car	7.8	0	60	27.69
17	Large Car	8.1	0	60	26.67
18	Small Car	7.4	0	60	29.19
19	Medium Car	7.2	0	60	30.00
20	Large Car	8.3	0	60	26.02

Left Turn Movement for 63m inscribed diameter roundabout

Test	Vehicle	Travel Time (s)	Approach Speed (km/h)	Distance (m)	Average Cruise Speed (km/h)
1	Small Car	3.9	0	19	17.54
2	Large Car	4.1	0	19	16.68
3	Large Car	4.2	0	19	16.29
4	Medium Car	4.1	0	19	16.68
5	Large Car	4.5	0	19	15.20
6	Large Car	4.6	0	19	14.87
7	Large Car	4.3	0	19	15.91
8	Large Car	4.1	0	19	16.68
9	Small Car	4.0	0	19	17.10
10	Small Car	3.8	0	19	18.00
11	Large Car	4.2	0	19	16.29
12	Large Car	4.2	0	19	16.29
13	Large Car	4.4	0	19	15.55
14	Large Car	3.9	0	19	17.54
15	Medium Car	4.0	0	19	17.10
16	Large Car	4.2	0	19	16.29
17	Medium Car	4.3	0	19	15.91
18	Large Car	4.6	0	19	14.87
19	Large Car	4.2	0	19	16.29
20	Large Car	4.4	0	19	15.55

APPENDIX D – DIAGRAMATIC VIEW OF UK PHASE SEQUENCE 60 SECOND PHASE



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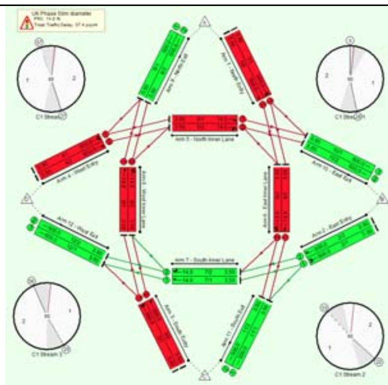

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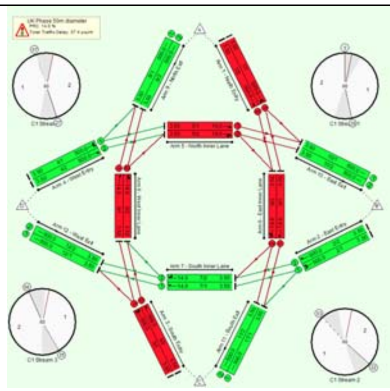

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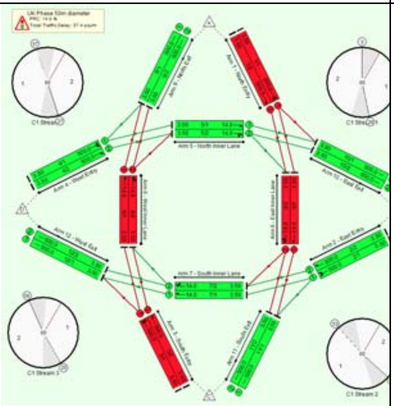

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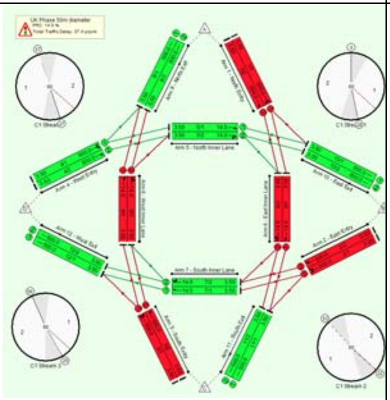

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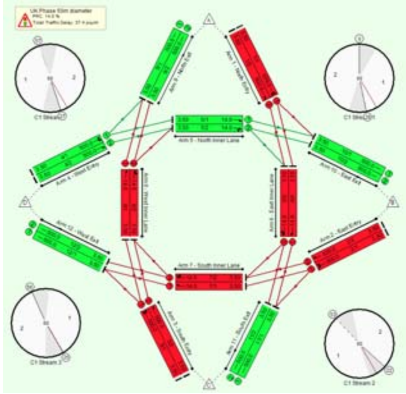

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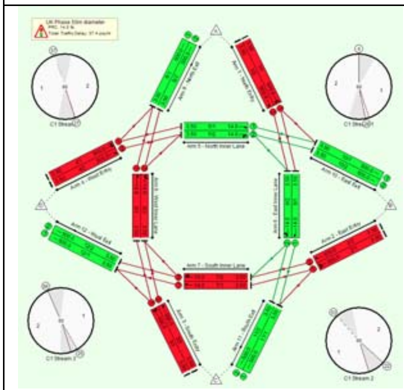

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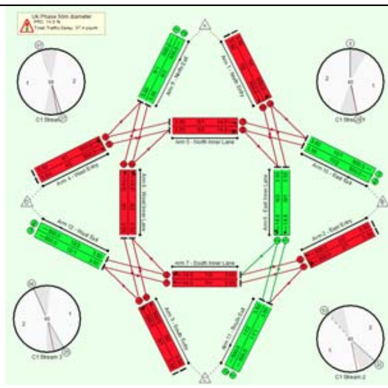

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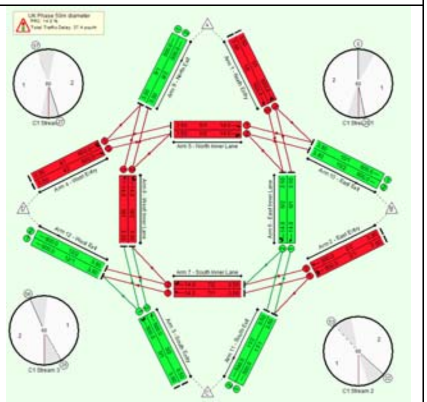

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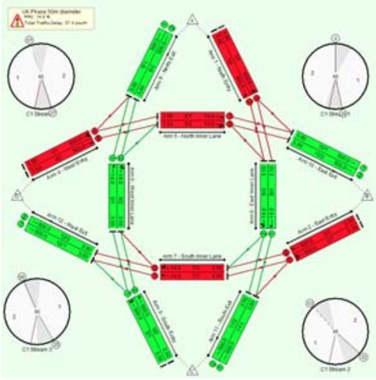
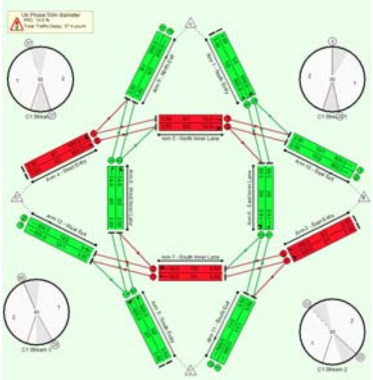
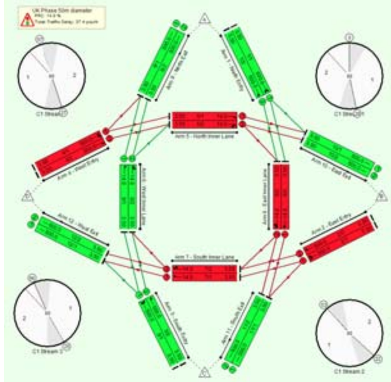
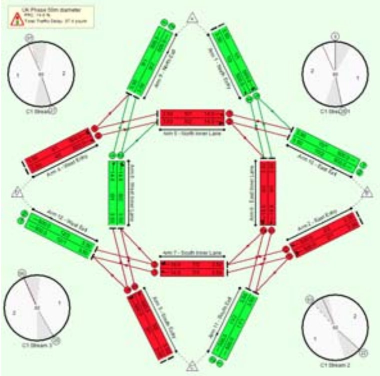
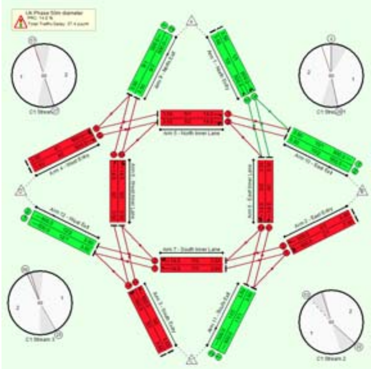
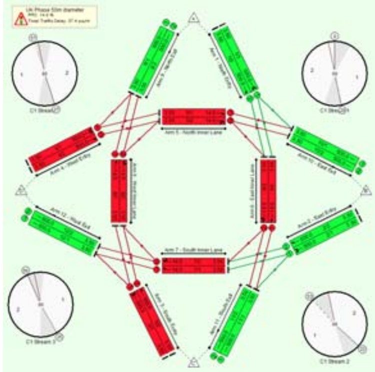
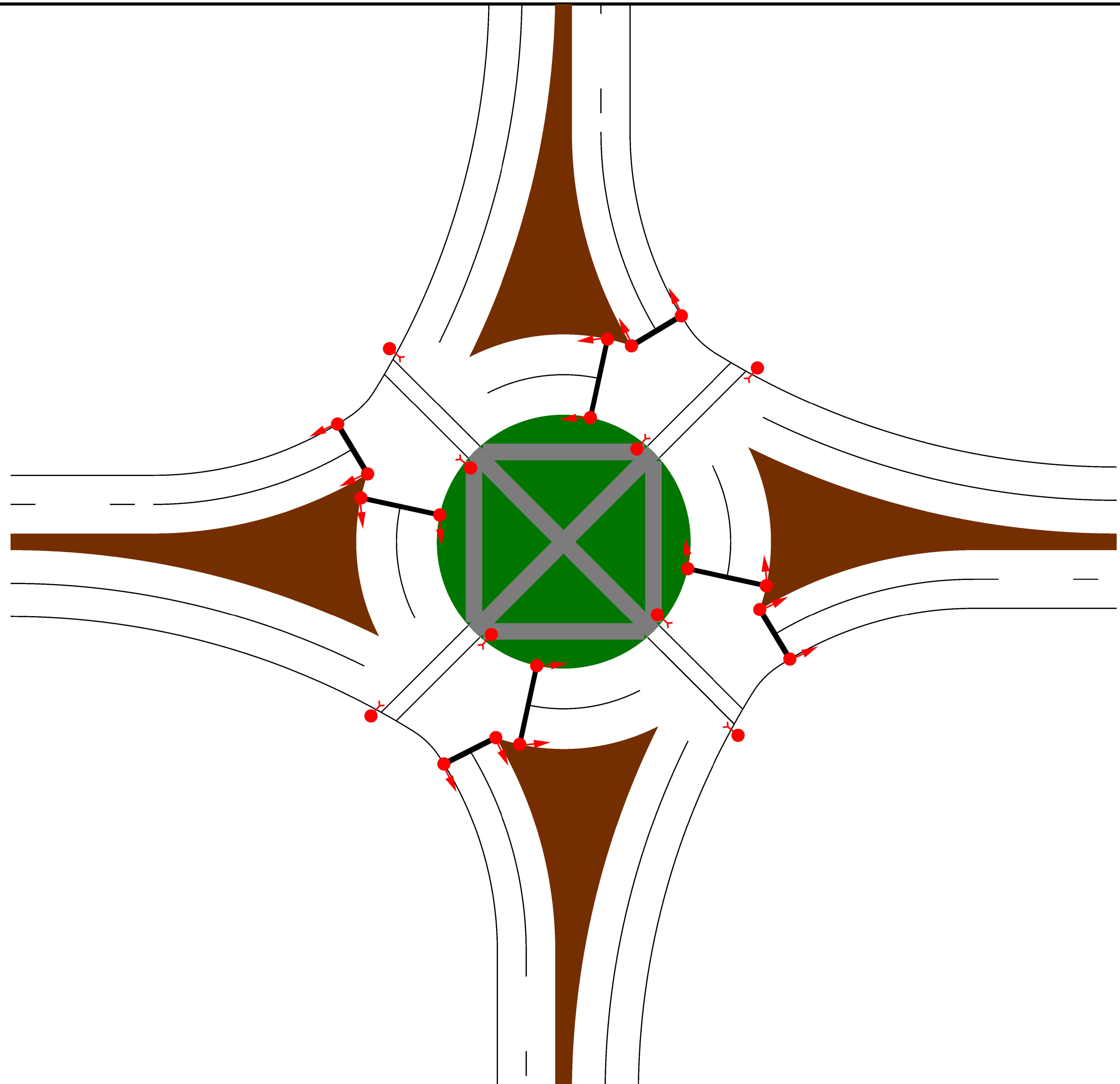
 32 seconds	 33 seconds	 53 seconds
 56 seconds	 57 seconds	 58 seconds

APPENDIX E – SCALE A3 DRAWINGS OF ROUNDABOUT MODELS



No.	Amendment Description	Initials	Date

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Coordinate System: MGA Zone 56

Height Datum: A.H.D.

EVALUATION OF THE CAPACITY OF SIGNALISED TWO LANE ROUNDABOUTS

UNIVERSITY OF SOUTHERN QUEENSLAND

50m SIGNALISED ROUNDABOUT TO AUSTRAOD 2011 STANDARDS

RESEARCH PROJECT 2012

DATE: 25/10/2012

DRAWING: Roundabouts.dgn

STUDENT: JARROD TAYLOR

Page 119

FilePath : H:\Uni\Research Project\Microstation drawings\Roundabouts.dgn

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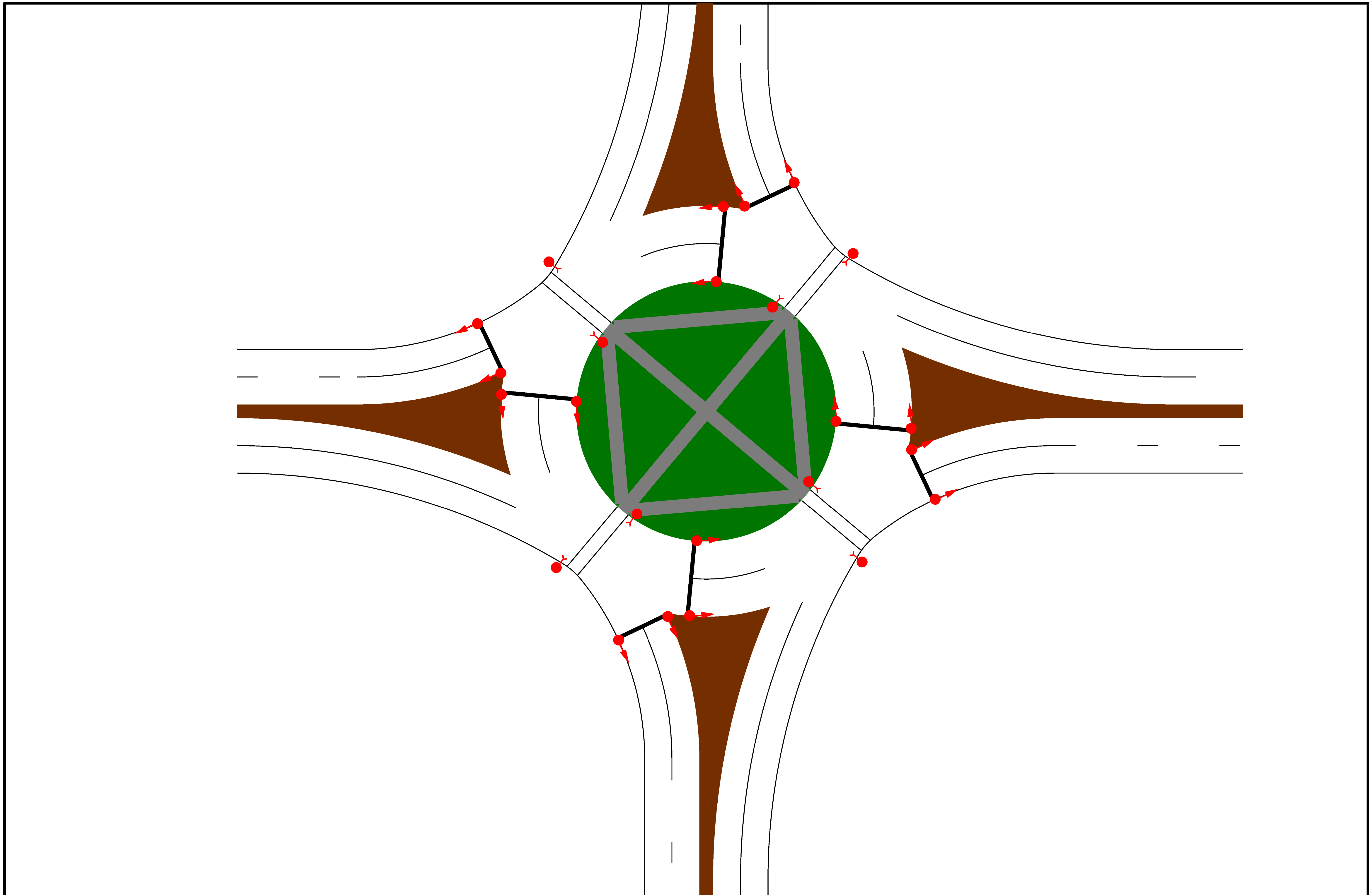

No.	Amendment Description	Initials	Date
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SCALES

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SCALE 1:500m

Coordinate System: MGA Zone 56

Height Datum: A.H.D.

EVALUATION OF THE CAPACITY OF SIGNALISED TWO LANE ROUNDABOUTS

UNIVERSITY OF SOUTHERN QUEENSLAND

60m SIGNALISED ROUNDABOUT TO AUSTRAOD 2011 STANDARDS

RESEARCH PROJECT 2012

DATE: 25/10/2012

DRAWING: Roundabouts.dgn

STUDENT: JARROD TAYLOR

Page 120

FilePath : H:\Uni\Research Project\Microstation drawings\Roundabouts.dgn
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APPENDIX F – LINSIG & EXCEL STANDARD PHASING RESULTS

Table F.1 – Capacity values for 50m inscribed diameter LinSig model 60s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**95.7%**	**73.3**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**95.7%**	**73.3**	-	-
1/1	South Entry Left Ahead	U	A	1	13	402	1800	420	95.7%	9.0	80.8	13.1
1/2	South Entry Ahead Right	U	A	1	13	402	1800	420	95.7%	9.0	80.8	13.1
2/1	North Entry Left Ahead	U	B	1	13	402	1800	420	95.7%	9.0	80.8	13.1
2/2	North Entry Right Ahead	U	B	1	13	402	1800	420	95.7%	9.0	80.8	13.1
3/1	East Entry Ahead Left	U	C	1	13	402	1800	420	95.7%	9.0	80.8	13.1
3/2	East Entry Ahead Right	U	C	1	13	402	1800	420	95.7%	9.0	80.8	13.1
4/1	West Entry Left Ahead	U	D	1	13	402	1800	420	95.7%	9.0	80.8	13.1
4/2	West Entry Ahead Right	U	D	1	13	402	1800	420	95.7%	9.0	80.8	13.1

Table F.2 – Capacity values for 50m inscribed diameter LinSig model 75s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**94.9%**	**83.7**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**94.9%**	**83.7**	-	-
1/1	South Entry Left Ahead	U	A	1	16	410	1800	432	94.7%	9.1	79.8	14.2
1/2	South Entry Ahead Right	U	A	1	16	409	1800	432	94.9%	9.2	80.9	14.3
2/1	North Entry Left Ahead	U	B	1	17	409	1800	432	94.7%	9.1	79.8	14.2
2/2	North Entry Right Ahead	U	B	1	17	410	1800	432	94.9%	9.2	80.9	14.3
3/1	East Entry Ahead Left	U	C	1	17	409	1800	432	94.7%	9.1	79.8	14.2
3/2	East Entry Ahead Right	U	C	1	17	410	1800	432	94.9%	9.2	80.9	14.3
4/1	West Entry Left Ahead	U	D	1	17	409	1800	432	94.7%	9.1	79.8	14.2
4/2	West Entry Ahead Right	U	D	1	17	410	1800	432	94.9%	9.2	80.9	14.3

C1 PRC for Signalled Lanes (%): -11.7 Total Delay for Signalled Lanes (pcuHr): 82.53 Cycle Time (s): 75
PRC Over All Lanes (%): -11.7 Total Delay Over All Lanes(pcuHr): 83.71

Table F.3 – Capacity values for 50m inscribed diameter LinSig model 90s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**93.9%**	**87.6**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**93.9%**	**87.6**	-	-
1/1	South Entry Left Ahead	U	A	1	21	412	1800	440	93.6%	9.1	79.9	15.4
1/2	South Entry Ahead Right	U	A	1	21	413	1800	440	93.9%	9.3	80.8	15.5
2/1	North Entry Left Ahead	U	B	1	21	412	1800	440	93.6%	9.1	79.9	15.4
2/2	North Entry Right Ahead	U	B	1	21	413	1800	440	93.9%	9.3	80.8	15.5
3/1	East Entry Ahead Left	U	C	1	20	412	1800	440	93.6%	9.1	79.9	15.4
3/2	East Entry Ahead Right	U	C	1	20	413	1800	440	93.9%	9.3	80.8	15.5
4/1	West Entry Left Ahead	U	D	1	20	412	1800	440	93.6%	9.1	79.9	15.4
4/2	West Entry Ahead Right	U	D	1	20	413	1800	440	93.9%	9.3	80.8	15.5

C1 PRC for Signalled Lanes (%): -9.3 Total Delay for Signalled Lanes (pcuHr): 86.37 Cycle Time (s): 90
PRC Over All Lanes (%): -9.3 Total Delay Over All Lanes(pcuHr): 87.56

Table F.4 – Capacity values for 50m inscribed diameter LinSig model 105s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**93.3%**	**75.0**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**93.3%**	**75.0**	-	-
1/1	South Entry Left Ahead	U	A	1	25	415	1800	446	93.1%	9.5	78.7	16.8
1/2	South Entry Ahead Right	U	A	1	25	416	1800	446	93.3%	9.7	79.6	17.0
2/1	North Entry Left Ahead	U	B	1	24	415	1800	446	93.1%	9.5	78.7	16.8
2/2	North Entry Right Ahead	U	B	1	24	416	1800	446	93.3%	9.7	79.6	17.0
3/1	East Entry Ahead Left	U	C	1	24	415	1800	446	93.1%	9.5	78.7	16.8
3/2	East Entry Ahead Right	U	C	1	24	416	1800	446	93.3%	9.7	79.6	17.0
4/1	West Entry Left Ahead	U	D	1	24	415	1800	446	93.1%	9.5	78.7	16.8
4/2	West Entry Ahead Right	U	D	1	24	416	1800	446	93.3%	9.7	79.6	17.0

C1 PRC for Signalled Lanes (%): -3.7 Total Delay for Signalled Lanes (pcuHr): 73.82 Cycle Time (s): 105
PRC Over All Lanes (%): -3.7 Total Delay Over All Lanes(pcuHr): 75.02

Table F.5 – Capacity values for 50m inscribed diameter LinSig model 60s phase time no all-red interval Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**96.7%**	**83.0**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**96.7%**	**83.0**	-	-
1/1	South Entry Left Ahead	U	A	1	15	463	1800	480	96.5%	10.1	78.6	14.9
1/2	South Entry Ahead Right	U	A	1	15	464	1800	480	96.7%	10.3	79.8	15.1
2/1	North Entry Left Ahead	U	B	1	15	463	1800	480	96.5%	10.1	78.6	14.9
2/2	North Entry Right Ahead	U	B	1	15	464	1800	480	96.7%	10.3	79.8	15.1
3/1	East Entry Ahead Left	U	C	1	15	463	1800	480	96.5%	10.1	78.6	14.9
3/2	East Entry Ahead Right	U	C	1	15	464	1800	480	96.7%	10.3	79.8	15.1
4/1	West Entry Left Ahead	U	D	1	15	463	1800	480	96.5%	10.1	78.6	14.9
4/2	West Entry Ahead Right	U	D	1	15	464	1800	480	96.7%	10.3	79.8	15.1

Table F.6 – Capacity values for 50m inscribed diameter 3 second clearance time Excel values Semi Rural / Urban Environment

Saturation flow	1800	veh/hr			
Cycle time	60	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	16	16	16	16	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q one lane (veh/hr)	480	480	480	480	**1920**
Q two lanes (veh/hr)	960	960	960	960	**3840**
Control Delay (s)	15	15	15	15	**45**

Saturation flow	1800	veh/hr			
Cycle time	90	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	23.5	23.5	23.5	23.5	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	470	470	470	470	**1880**
Q (two lanes)	940	940	940	940	**3760**
Control Delay (s)	23	23	23	23	**68**

Saturation flow	1800	veh/hr			
Cycle time	75	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	19.75	19.75	19.75	19.75	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	474	474	474	474	**1896**
Q (two lanes)	948	948	948	948	**3792**
Control Delay (s)	19	19	19	19	**56**

Saturation flow	1800	veh/hr			
Cycle time	105	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	27.25	27.25	27.25	27.25	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	467	467	467	467	**1869**
Q (two lanes)	934	934	934	934	**3737**
Control Delay (s)	26	26	26	26	**79**

Table F.7 – Capacity values for 50m inscribed diameter LinSig model 60s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**95.9%**	**71.8**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**95.9%**	**71.8**	-	-
1/1	South Entry Left Ahead	U	A	1	13	424	1900	443	95.6%	9.2	78.2	13.5
1/2	South Entry Ahead Right	U	A	1	13	425	1900	443	95.9%	9.4	79.5	13.7
2/1	North Entry Left Ahead	U	B	1	13	424	1900	443	95.6%	9.2	78.2	13.5
2/2	North Entry Right Ahead	U	B	1	13	425	1900	443	95.9%	9.4	79.5	13.7
3/1	East Entry Ahead Left	U	C	1	13	424	1900	443	95.6%	9.2	78.2	13.5
3/2	East Entry Ahead Right	U	C	1	13	425	1900	443	95.9%	9.4	79.5	13.7
4/1	West Entry Left Ahead	U	D	1	13	424	1900	443	95.6%	9.2	78.2	13.5
4/2	West Entry Ahead Right	U	D	1	13	425	1900	443	95.9%	9.4	79.5	13.7

C1 PRC for Signalled Lanes (%): -6.5 Total Delay for Signalled Lanes (pcuHr): 70.61 Cycle Time (s): 60
PRC Over All Lanes (%): -6.5 Total Delay Over All Lanes(pcuHr): 71.76

Table F.8 – Capacity values for 50m inscribed diameter LinSig model 75s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**95.2%**	**88.1**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**95.2%**	**88.1**	-	-
1/1	South Entry Left Ahead	U	A	1	17	433	1900	456	95.0%	9.5	79.1	14.9
1/2	South Entry Ahead Right	U	A	1	17	434	1900	456	95.2%	9.7	80.2	15.1
2/1	North Entry Left Ahead	U	B	1	17	433	1900	456	95.0%	9.5	79.1	14.9
2/2	North Entry Right Ahead	U	B	1	17	434	1900	456	95.2%	9.7	80.2	15.1
3/1	East Entry Ahead Left	U	C	1	17	433	1900	456	95.0%	9.5	79.1	14.9
3/2	East Entry Ahead Right	U	C	1	17	434	1900	456	95.2%	9.7	80.2	15.1
4/1	West Entry Left Ahead	U	D	1	17	433	1900	456	95.0%	9.5	79.1	14.9
4/2	West Entry Ahead Right	U	D	1	17	434	1900	456	95.2%	9.7	80.2	15.1

C1 PRC for Signalled Lanes (%): -12.0 Total Delay for Signalled Lanes (pcuHr): 86.96 Cycle Time (s): 75
PRC Over All Lanes (%): -12.0 Total Delay Over All Lanes(pcuHr): 88.14

Table F.9 – Capacity values for 50m inscribed diameter LinSig model 90s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**94.3%**	**94.1**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**94.3%**	**94.1**	-	-
1/1	South Entry Left Ahead	U	A	1	21	438	1900	464	94.3%	9.8	80.8	16.5
1/2	South Entry Ahead Right	U	A	1	21	438	1900	464	94.3%	9.8	80.8	16.5
2/1	North Entry Left Ahead	U	B	1	21	438	1900	464	94.3%	9.8	80.8	16.5
2/2	North Entry Right Ahead	U	B	1	21	438	1900	464	94.3%	9.8	80.8	16.5
3/1	East Entry Ahead Left	U	C	1	21	438	1900	464	94.3%	9.8	80.8	16.5
3/2	East Entry Ahead Right	U	C	1	21	438	1900	464	94.3%	9.8	80.8	16.5
4/1	West Entry Left Ahead	U	D	1	21	438	1900	464	94.3%	9.8	80.8	16.5
4/2	West Entry Ahead Right	U	D	1	21	438	1900	464	94.3%	9.8	80.8	16.5

C1 PRC for Signalled Lanes (%): -9.8 Total Delay for Signalled Lanes (pcuHr): 92.91 Cycle Time (s): 90
PRC Over All Lanes (%): -9.8 Total Delay Over All Lanes(pcuHr): 94.11

Table F.10 – Capacity values for 50m inscribed diameter LinSig model 105s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**93.5%**	**78.2**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**93.5%**	**78.2**	-	-
1/1	South Entry Left Ahead	U	A	1	25	439	1900	470	93.3%	9.9	80.6	17.7
1/2	South Entry Ahead Right	U	A	1	25	440	1900	470	93.5%	10.1	81.4	17.8
2/1	North Entry Left Ahead	U	B	1	24	439	1900	470	93.3%	9.9	80.6	17.7
2/2	North Entry Right Ahead	U	B	1	24	440	1900	470	93.5%	10.1	81.4	17.8
3/1	East Entry Ahead Left	U	C	1	24	439	1900	470	93.3%	9.9	80.6	17.7
3/2	East Entry Ahead Right	U	C	1	24	440	1900	470	93.5%	10.1	81.4	17.8
4/1	West Entry Left Ahead	U	D	1	24	439	1900	470	93.3%	9.9	80.6	17.7
4/2	West Entry Ahead Right	U	D	1	24	440	1900	470	93.5%	10.1	81.4	17.8

C1 PRC for Signalled Lanes (%): -3.9 Total Delay for Signalled Lanes (pcuHr): 77.00 Cycle Time (s): 105
PRC Over All Lanes (%): -3.9 Total Delay Over All Lanes(pcuHr): 78.20

Table F.11 – Capacity values for 50m inscribed diameter LinSig model 60s phase time no all-red interval Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**97.1%**	**89.3**	-	-
50m Signalised Roundabout	-	-	-	-	-	-	-	-	**97.1%**	**89.3**	-	-
1/1	South Entry Left Ahead	U	A	1	15	492	1900	507	97.1%	11.0	80.4	16.1
1/2	South Entry Ahead Right	U	A	1	15	492	1900	507	97.1%	11.0	80.4	16.1
2/1	North Entry Left Ahead	U	B	1	15	492	1900	507	97.1%	11.0	80.4	16.1
2/2	North Entry Right Ahead	U	B	1	15	492	1900	507	97.1%	11.0	80.4	16.1
3/1	East Entry Ahead Left	U	C	1	15	492	1900	507	97.1%	11.0	80.4	16.1
3/2	East Entry Ahead Right	U	C	1	15	492	1900	507	97.1%	11.0	80.4	16.1
4/1	West Entry Left Ahead	U	D	1	15	492	1900	507	97.1%	11.0	80.4	16.1
4/2	West Entry Ahead Right	U	D	1	15	492	1900	507	97.1%	11.0	80.4	16.1

Table F.12 – Capacity values for 50m inscribed diameter 3 second clearance time Excel values Urban Environment

Saturation flow	1900	veh/hr			
Cycle time	60	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	16	16	16	16	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q one lane (veh/hr)	507	507	507	507	**2027**
Q two lanes (veh/hr)	1013	1013	1013	1013	**4053**
Control Delay (s)	15	15	15	15	**45**

Saturation flow	1900	veh/hr			
Cycle time	90	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	23.5	23.5	23.5	23.5	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	496	496	496	496	**1984**
Q (two lanes)	992	992	992	992	**3969**
Control Delay (s)	23	23	23	23	**68**

Saturation flow	1900	veh/hr			
Cycle time	75	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	19.75	19.75	19.75	19.75	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	500	500	500	500	**2001**
Q (two lanes)	1001	1001	1001	1001	**4003**
Control Delay (s)	19	19	19	19	**56**

Saturation flow	1900	veh/hr			
Cycle time	105	sec			
Clearance time	-1	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	27.25	27.25	27.25	27.25	
Proportion of time (u)	0.26	0.26	0.26	0.26	
Q (one lane)	493	493	493	493	**1972**
Q (two lanes)	986	986	986	986	**3945**
Control Delay (s)	26	26	26	26	**79**

Table F.13 – Capacity values for 60m inscribed diameter 3 second clearance time Excel values Semi-rural / Urban Environment

Saturation flow	1800	veh/hr			
Cycle time	60	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	17	17	17	17	
Proportion of time (u)	0.28	0.28	0.28	0.28	
Q one lane (veh/hr)	510	510	510	510	**2040**
Q two lanes (veh/hr)	1020	1020	1020	1020	**4080**
Control Delay (s)	15	15	15	15	**45**

Saturation flow	1800	veh/hr			
Cycle time	90	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	24.5	24.5	24.5	24.5	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q (one lane)	490	490	490	490	**1960**
Q (two lanes)	980	980	980	980	**3920**
Control Delay (s)	23	23	23	23	**68**

Saturation flow	1800	veh/hr			
Cycle time	75	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	20.75	20.75	20.75	20.75	
Proportion of time (u)	0.28	0.28	0.28	0.28	
Q (one lane)	498	498	498	498	**1992**
Q (two lanes)	996	996	996	996	**3984**
Control Delay (s)	19	19	19	19	**56**

Saturation flow	1800	veh/hr			
Cycle time	105	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	28.25	28.25	28.25	28.25	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q (one lane)	484	484	484	484	**1937**
Q (two lanes)	969	969	969	969	**3874**
Control Delay (s)	26	26	26	26	**79**

Table F.14 – Capacity values for 60m inscribed diameter 3 second clearance time Excel values Urban Environment

Saturation flow	1900	veh/hr			
Cycle time	60	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	17	17	17	17	
Proportion of time (u)	0.28	0.28	0.28	0.28	
Q one lane (veh/hr)	538	538	538	538	**2153**
Q two lanes (veh/hr)	1077	1077	1077	1077	**4307**
Control Delay (s)	15	15	15	15	**45**

Saturation flow	1900	veh/hr			
Cycle time	90	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	24.5	24.5	24.5	24.5	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q (one lane)	517	517	517	517	**2069**
Q (two lanes)	1034	1034	1034	1034	**4138**
Control Delay (s)	23	23	23	23	**68**

Saturation flow	1900	veh/hr			
Cycle time	75	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	20.75	20.75	20.75	20.75	
Proportion of time (u)	0.28	0.28	0.28	0.28	
Q (one lane)	526	526	526	526	**2103**
Q (two lanes)	1051	1051	1051	1051	**4205**
Control Delay (s)	19	19	19	19	**56**

Saturation flow	1900	veh/hr			
Cycle time	105	sec			
Clearance time	-2	sec			
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Effective Green time (s)	28.25	28.25	28.25	28.25	
Proportion of time (u)	0.27	0.27	0.27	0.27	
Q (one lane)	511	511	511	511	**2045**
Q (two lanes)	1022	1022	1022	1022	**4090**
Control Delay (s)	26	26	26	26	**79**

APPENDIX G – LINSIG UK PHASING RESULTS 50m INSCRIBED DIAMETER

Table G.1 – Controlled delay for journey times LinSig model 60s phase time Semi Rural / Urban Environment

Route Number	Origin Zone	Origin Lane	Destination Zone	Destination Lane	Time (s)
1	A	1/1	B	10/1	57.14
3	A	1/1	C	11/1	60.14
4	A	1/2	C	11/2	59.89
5	B	2/1	C	11/1	57.14
6	C	3/1	A	9/1	60.14
7	C	3/2	A	9/2	59.89
9	B	2/1	D	12/1	60.14
10	B	2/2	D	12/2	59.89
11	C	3/1	D	12/1	57.14
12	D	4/1	A	9/1	57.14
13	D	4/1	B	10/1	60.14
14	D	4/2	B	10/2	59.89
15	A	1/2	D	12/2	70.86
17	C	3/2	B	10/2	72.86
21	D	4/2	C	11/2	69.88
23	B	2/2	A	9/2	73.86
28	D	4/2	C	11/1	69.87
29	A	1/2	D	12/1	70.87
34	B	2/2	A	9/1	73.87
39	C	3/2	B	10/1	72.87

Table G.2 – Capacity values LinSig model 60s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**90.60%**	**58.2**	-	-
UK Phase 50m diameter	-	-	-	-	-	-	-	-	**90.60%**	**58.2**	-	-
1/1	North Entry Ahead Ahead2	U	B	1	15	462	1800	510	90.60%	6.8	52.8	11.4
1/2	North Entry Ahead	U	B	1	15	462	1800	510	90.60%	6.8	52.8	11.4
2/1	East Entry Ahead Ahead2	U	D	1	15	462	1800	510	90.60%	6.8	52.8	11.4
2/2	East Entry Ahead	U	D	1	15	462	1800	510	90.60%	6.8	52.8	11.4
3/1	South Entry Ahead Ahead2	U	F	1	15	462	1800	510	90.60%	6.8	52.8	11.4
3/2	South Entry Ahead	U	F	1	15	462	1800	510	90.60%	6.8	52.8	11.4
4/1	West Entry Ahead Ahead2	U	H	1	15	462	1800	510	90.60%	6.8	52.8	11.4
4/2	West Entry Ahead	U	H	1	15	462	1800	510	90.60%	6.8	52.8	11.4
5/1	North Inner Lane Ahead	U	A	1	35	301	1800	1110	27.10%	0.4	4.3	2.4
5/2	North Inner Lane Right Ahead	U	A	1	35	623	1800	1110	56.10%	0.4	2.3	2.7
6/1	East Inner Lane Ahead	U	C	1	35	300	1800	1110	27.00%	0.2	2.8	2.4
6/2	East Inner Lane Right Ahead	U	C	1	35	624	1800	1110	56.20%	0.3	1.6	2.7
7/1	South Inner Lane Ahead	U	E	1	35	301	1800	1110	27.10%	0.3	3.3	2.4
7/2	South Inner Lane Right Ahead	U	E	1	35	623	1800	1110	56.10%	0.3	1.8	2.7

8/1	West Inner Lane Ahead	U	G	1	35	301	1800	1110	27.10%	0.4	4.8	2.4
8/2	West Inner Lane Right Ahead	U	G	1	35	623	1800	1110	56.10%	0.4	2.6	2.7

Table G.3 – Controlled delay for journey times LinSig model 60s phase Urban Environment

Route Number	Origin Zone	Origin Lane	Destination Zone	Destination Lane	Time (s)
1	A	1/1	B	10/1	50.82
3	A	1/1	C	11/1	53.80
4	A	1/2	C	11/2	54.07
5	B	2/1	C	11/1	46.70
6	C	3/1	A	9/1	49.71
7	C	3/2	A	9/2	49.46
9	B	2/1	D	12/1	49.71
10	B	2/2	D	12/2	49.46
11	C	3/1	D	12/1	46.71
12	D	4/1	A	9/1	46.71
13	D	4/1	B	10/1	49.71
14	D	4/2	B	10/2	49.46
15	A	1/2	D	12/2	65.07
17	C	3/2	B	10/2	62.68
21	D	4/2	C	11/2	59.67
23	B	2/2	A	9/2	63.68
28	D	4/2	C	11/1	59.68
29	A	1/2	D	12/1	65.06
34	B	2/2	A	9/1	63.67
39	C	3/2	B	10/1	62.67

Table G.4 – Capacity values LinSig model 60s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**88.60%**	**48.7**	**-**	**-**
UK Phase 50m diameter	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**88.60%**	**48.7**	**-**	**-**
1/1	North Entry Ahead Ahead2	U	B	1	15	447	1800	510	87.60%	5.8	46.4	10.3
1/2	North Entry Ahead	U	B	1	15	477	1900	538	88.60%	6.2	46.9	11
2/1	East Entry Ahead Ahead2	U	D	1	15	462	1900	538	85.80%	5.4	42.3	10
2/2	East Entry Ahead	U	D	1	15	462	1900	538	85.80%	5.4	42.3	10
3/1	South Entry Ahead Ahead2	U	F	1	15	462	1900	538	85.80%	5.4	42.3	10
3/2	South Entry Ahead	U	F	1	15	462	1900	538	85.80%	5.4	42.3	10
4/1	West Entry Ahead Ahead2	U	H	1	15	462	1900	538	85.80%	5.4	42.3	10
4/2	West Entry Ahead	U	H	1	15	462	1900	538	85.80%	5.4	42.3	10
5/1	North Inner Lane Ahead	U	A	1	35	299	1900	1172	25.50%	0.4	4.3	2.4
5/2	North Inner Lane Right Ahead	U	A	1	35	625	1900	1172	53.30%	0.4	2.4	2.7
6/1	East Inner Lane Ahead	U	C	1	35	285	1900	1172	24.30%	0.2	3.1	2.4
6/2	East Inner Lane Right Ahead	U	C	1	35	639	1900	1172	54.50%	0.3	1.6	2.7
7/1	South Inner Lane Ahead	U	E	1	35	299	1900	1172	25.50%	0.3	3.3	2.4
7/2	South Inner Lane Right Ahead	U	E	1	35	625	1900	1172	53.30%	0.3	1.8	2.7

8/1	West Inner Lane Ahead	U	G	1	35	299	1900	1172	25.50%	0.4	4.8	2.4
8/2	West Inner Lane Right Ahead	U	G	1	35	625	1900	1172	53.30%	0.5	2.7	2.7

APPENDIX H – LINSIG UK PHASING RESULTS 60m INSCRIBED DIAMETER

Table H.1 – Controlled delay for journey times LinSig model 60s phase time Semi Rural / Urban Environment

Route Number	Origin Zone	Origin Lane	Destination Zone	Destination Lane	Time (s)
1	A	1/1	B	10/1	41.04
3	A	1/1	C	11/1	45.04
4	A	1/2	C	11/2	45.00
5	B	2/1	C	11/1	47.12
6	C	3/1	A	9/1	45.04
7	C	3/2	A	9/2	45.00
9	B	2/1	D	12/1	51.12
10	B	2/2	D	12/2	51.18
11	C	3/1	D	12/1	41.04
12	D	4/1	A	9/1	47.12
13	D	4/1	B	10/1	51.12
14	D	4/2	B	10/2	51.18
15	A	1/2	D	12/2	55.91
17	C	3/2	B	10/2	55.91
21	D	4/2	C	11/2	62.11
23	B	2/2	A	9/2	60.18
28	D	4/2	C	11/1	62.11
29	A	1/2	D	12/1	55.89
34	B	2/2	A	9/1	60.18
39	C	3/2	B	10/1	55.89

Table H.2 – Capacity values LinSig model 60s phase time Semi Rural / Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**81.8%**	**34.2**	-	-
UK Phase 50m diameter	-	-	-	-	-	-	-	-	**81.8%**	**34.2**	-	-
1/1	North Entry Ahead Ahead2	U	B	1	14	367	1800	480	76.5%	3.6	35.8	7.2
1/2	North Entry Ahead	U	B	1	14	368	1800	480	76.7%	3.7	35.9	7.2
2/1	East Entry Ahead Ahead2	U	D	1	13	367	1800	450	81.6%	4.3	41.8	7.8
2/2	East Entry Ahead	U	D	1	13	368	1800	450	81.8%	4.3	42.1	7.9
3/1	South Entry Ahead Ahead2	U	F	1	14	367	1800	480	76.5%	3.6	35.8	7.2
3/2	South Entry Ahead	U	F	1	14	368	1800	480	76.7%	3.7	35.9	7.2
4/1	West Entry Ahead Ahead2	U	H	1	13	367	1800	450	81.6%	4.3	41.8	7.8
4/2	West Entry Ahead	U	H	1	13	368	1800	450	81.8%	4.3	42.1	7.9
5/1	North Inner Lane Ahead	U	A	1	36	238	1800	1140	20.9%	0.2	2.8	1.8
5/2	North Inner Lane Right Ahead	U	A	1	36	497	1800	1140	43.6%	0.2	1.5	2.1
6/1	East Inner Lane Ahead	U	C	1	37	239	1800	1170	20.4%	0.2	2.8	1.9
6/2	East Inner Lane Right Ahead	U	C	1	37	496	1800	1170	42.4%	0.2	1.5	2.1
7/1	South Inner Lane Ahead	U	E	1	36	238	1800	1140	20.9%	0.2	2.8	1.8
7/2	South Inner Lane Right Ahead	U	E	1	36	497	1800	1140	43.6%	0.2	1.5	2.1

8/1	West Inner Lane Ahead	U	G	1	37	238	1800	1170	20.3%	0.1	1.9	1.7
8/2	West Inner Lane Right Ahead	U	G	1	37	497	1800	1170	42.5%	0.1	1.0	2.0

Table H.3 – Controlled delay for journey times LinSig model 60s phase time Urban Environment

Route Number	Origin Zone	Origin Lane	Destination Zone	Destination Lane	Time (s)
1	A	1/1	B	10/1	37.93
3	A	1/1	C	11/1	41.93
4	A	1/2	C	11/2	41.85
5	B	2/1	C	11/1	42.36
6	C	3/1	A	9/1	41.93
7	C	3/2	A	9/2	41.85
9	B	2/1	D	12/1	46.36
10	B	2/2	D	12/2	46.34
11	C	3/1	D	12/1	37.93
12	D	4/1	A	9/1	42.36
13	D	4/1	B	10/1	46.36
14	D	4/2	B	10/2	46.34
15	A	1/2	D	12/2	52.91
17	C	3/2	B	10/2	52.91
21	D	4/2	C	11/2	57.45
23	B	2/2	A	9/2	55.53
28	D	4/2	C	11/1	57.46
29	A	1/2	D	12/1	52.92
34	B	2/2	A	9/1	55.55
39	C	3/2	B	10/1	52.92

Table H.4 – Capacity values LinSig model 60s phase time Urban Environment

Item	Lane Description	Lane Type	Full Phase	Num Greens	Total Green (s)	Demand Flow (pcu)	Sat Flow (pcu/Hr)	Capacity (pcu)	Deg Sat (%)	Total Delay (pcuHr)	Av. Delay Per PCU (s/pcu)	Mean Max Queue (pcu)
Network	-	-	-	-	-	-	-	-	**77.5%**	**31.0**	-	-
UK Phase 50m diameter	-	-	-	-	-	-	-	-	**77.5%**	**31.0**	-	-
1/1	North Entry Ahead Ahead2	U	B	1	14	367	1900	507	72.4%	3.3	32.7	6.8
1/2	North Entry Ahead	U	B	1	14	368	1900	507	72.6%	3.3	32.8	6.8
2/1	East Entry Ahead Ahead2	U	D	1	13	367	1900	475	77.3%	3.8	37.1	7.3
2/2	East Entry Ahead	U	D	1	13	368	1900	475	77.5%	3.8	37.2	7.3
3/1	South Entry Ahead Ahead2	U	F	1	14	367	1900	507	72.4%	3.3	32.7	6.8
3/2	South Entry Ahead	U	F	1	14	368	1900	507	72.6%	3.3	32.8	6.8
4/1	West Entry Ahead Ahead2	U	H	1	13	367	1900	475	77.3%	3.8	37.1	7.3
4/2	West Entry Ahead	U	H	1	13	368	1900	475	77.5%	3.8	37.2	7.3
5/1	North Inner Lane Ahead	U	A	1	36	238	1900	1203	19.8%	0.2	2.9	1.8
5/2	North Inner Lane Right Ahead	U	A	1	36	497	1900	1203	41.3%	0.2	1.6	2.0
6/1	East Inner Lane Ahead	U	C	1	37	238	1900	1235	19.3%	0.2	2.9	1.9
6/2	East Inner Lane Right Ahead	U	C	1	37	497	1900	1235	40.2%	0.2	1.6	2.1
7/1	South Inner Lane Ahead	U	E	1	36	238	1900	1203	19.8%	0.2	2.9	1.8
7/2	South Inner Lane Right Ahead	U	E	1	36	497	1900	1203	41.3%	0.2	1.6	2.0

8/1	West Inner Lane Ahead	U	G	1	37	238	1900	1235	19.3%	0.1	2.0	1.8
8/2	West Inner Lane Right Ahead	U	G	1	37	497	1900	1235	40.2%	0.2	1.1	2.0

APPENDIX I – UN-SIGNALISED ROUNDABOUT CAPACITIES

Table I.1 – Capacity of un-signalised roundabout based on uniform flow from HCM 2010

Circulating Flow (veh/hr)	Left Entry (veh/hr)	Right Entry (veh/hr)	One Leg Entry (veh/hr)	Total Entry (veh/hr)	Total Capacity (veh/hr)
1500	395	367	762	3049	4549
1750	332	304	636	2544	4294
2000	279	252	531	2123	4123
2250	234	209	443	1772	4022
2500	196	173	370	1479	3979
2750	165	144	309	1234	3984
3000	138	119	257	1030	4030
3250	116	99	215	860	4110
3500	98	82	179	717	4217

Table I.2 – Capacity of un-signalised roundabout based on uniform flow from Tan 2001

% of Left Turn	% of Through	% of Right Turn	Total Capacity (veh/hr)
33	33	33	4111

Table I.3 – Capacity of un-signalised roundabout based on variable flow from Tan 2001

% of Left Turn	% of Through	% of Right Turn	Total Capacity (veh/hr)
10	55	35	3649
15	55	30	3814
20	55	25	3994
25	55	20	4193
30	55	15	4412
35	55	10	4655
40	55	5	4927
% of Left Turn	**% of Through**	**% of Right Turn**	**Total Capacity (veh/hr)**
10	50	40	3571
15	50	35	3729
20	50	30	3902
25	50	25	4091
30	50	20	4299
35	50	15	4530
40	50	10	4787
% of Left Turn	**% of Through**	**% of Right Turn**	**Total Capacity (veh/hr)**
10	45	45	3497
15	45	40	3649
20	45	35	3814
25	45	30	3994
30	45	25	4193
35	45	20	4412
40	45	15	4655

% of Left Turn	% of Through	% of Right Turn	Total Capacity (veh/hr)
10	40	50	3426
15	40	45	3571
20	40	40	3729
25	40	35	3902
30	40	30	4091
35	40	25	4299
40	40	20	4530
% of Left Turn	**% of Through**	**% of Right Turn**	**Total Capacity (veh/hr)**
10	35	55	3358
15	35	50	3497
20	35	45	3649
25	35	40	3814
30	35	35	3994
35	35	30	4193
40	35	25	4412
% of Left Turn	**% of Through**	**% of Right Turn**	**Total Capacity (veh/hr)**
10	30	60	3293
15	30	55	3426
20	30	50	3571
25	30	45	3729
30	30	40	3902
35	30	35	4091
40	30	30	4299