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Differences between the AUSTROADS Roundabout Guide and aaSIDRA Roundabout Analysis Methods

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ABSTRACT

The roundabout capacity analysis method used in aaSIDRA was originally based on the method described in ARRB Special Report SR 45 (Troutbeck 1989) which was introduced into aaSIDRA with some variations and extensions (Akçelik and Troutbeck 1991). The SR 45 method was also incorporated into the AUSTROADS (1993) Roundabout Guide with some minor modifications (Troutbeck 1992). Subsequently, significant enhancements were introduced in various versions of aaSIDRA, including some important changes introduced in the latest version aaSIDRA 2.1, based on further research and development (Akcelik & Associates 2004; Akçelik 2003a, 2003b, 2004; Akçelik, Chung and Besley 1997, 1998). This paper presents a summary of the differences between the AUSTROADS Roundabout Guide and aaSIDRA methods for roundabout capacity and performance analysis, and discusses some important aspects of the analysis method where significant differences exist.

1. INTRODUCTION

Both the AUSTROADS Roundabout Guide (1993) and the aaSIDRA software package (Akcelik & Associates 2004) use *gap acceptance* techniques for roundabout capacity and performance analysis based on *empirical* models to estimate gap-acceptance parameters. As such, they differ from the method of estimating capacity directly from a regression model as used in the UK "empirical" model (Akçelik 1997, 2003a, 2004; Akçelik, Chung and Besley 1998; Brown 1995; Chard 1997) and the German regression model (Brilon, Wu and Bondzio 1997). In addition to the main aaSIDRA model for roundabout capacity and performance analysis, aaSIDRA offers several *alternative* capacity models for comparison purposes. *Figure 1.1* shows the relationships among roundabout analysis models related to the aaSIDRA model, or used in aaSIDRA as alternative models.

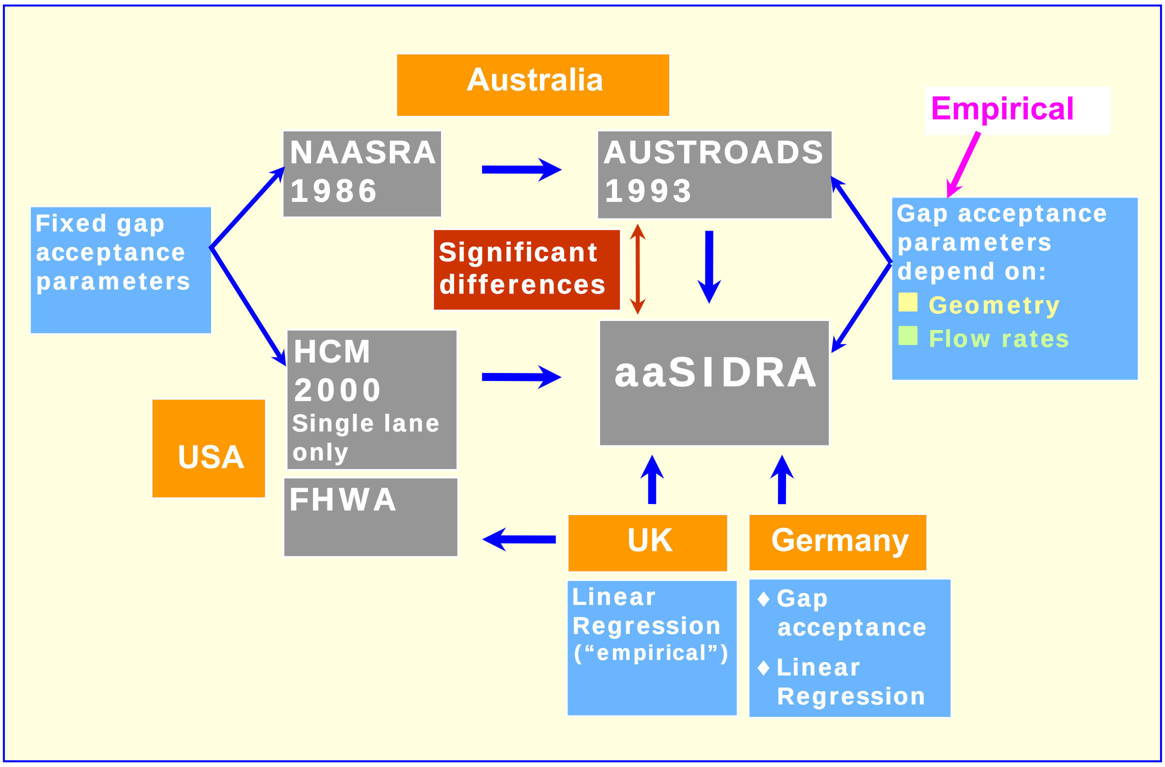

Figure 1.1 - Relationships among roundabout analysis models related to the aaSIDRA model, or used in aaSIDRA as alternative models

Complexities involved in intersection modelling (as in modelling of all traffic facilities) require representation of ***driver behaviour*** characteristics and ***road geometry*** conditions. The aaSIDRA and AUSTROADS roundabout capacity and performance analysis methods allow for the effects of driver behaviour through the use of gap-acceptance methodology, where the gap-acceptance parameters depend on roundabout geometry. The aaSIDRA and AUSTROADS methods are based on gap-acceptance methodology with an ***empirical*** base. They use gap-acceptance parameters calibrated using data from field surveys conducted at a large number of roundabouts in Australia. *Table 1.1* shows a summary of field data at 55 roundabout entry lanes used for this purpose. This is based on recent re-examination of the original data reported in Special Report SR 45 (data points not used in critical gap and follow-up headway regressions are excluded).

In contrast with the aaSIDRA and AUSTROADS methods:

- the UK and German linear regression methods primarily rely on the use of roundabout geometry parameters with no representation of driver behaviour other than what is implied by circulating flow rate effect, and
- the US Highway Capacity Manual (TRB 2000) method allows for driver behaviour using fixed gap-acceptance parameters with no allowance for roundabout geometry representation (except restriction to single-lane roundabouts).

Table 1.1

Australian roundabout survey data summary

	Total entry width (m)	No. of entry lanes	Average entry lane width (m)	Circul. width (m)	Inscribed Diameter (m)	Entry radius (m)	Conflict angle (°)
Minimum	3.7	1	3.20	6.5	16	4	0
Maximum	12.5	3	5.50	12.0	220	∞	80
Average	8.1	2	3.84	9.6	56	39.0	29
15th percentile	6.4	2	3.34	8.0	28	10.0	0
85th percentile	10.5	3	4.48	11.9	70	39.8	50
Count	55	55	55	55	55	55	55
	Follow-up Headway (s)	**Critical Gap (s)**	**Crit. Gap / Fol. Hw Ratio**	**Circul. flow (veh/h)**	**Total entry flow (veh/h)**	**Dominant lane flow (veh/h)**	**Subdom. lane flow (veh/h)**
Minimum	0.80	1.90	1.09	225	369	274	73
Maximum	3.55	7.40	3.46	2648	3342	2131	1211
Average	2.04	3.45	1.75	1066	1284	796	501
15th percentile	1.32	2.53	1.26	446	690	467	224
85th percentile	2.65	4.51	2.31	1903	1794	1002	732
Count	55	55	55	55	55	55	55

All models considered in *Figure 1.1* use the circulating flow rate as a key parameter in capacity estimation (capacity decreases with increased circulating flow rate). It may be considered that the circulating flow rate implies some indirect representation of driver behaviour. The old NAASRA (1986) and German gap-acceptance methods allow for driver behaviour through the use of gap-acceptance parameters with some allowance for roundabout geometry (the number of entry and circulating lanes).

The UK linear regression model employs a coarse method which is limited to aggregate representation of roundabout approaches with no parameters representing approach or circulating road lanes.

Importantly, aaSIDRA gap acceptance models are used not only for ***capacity*** estimation, but also for the estimation of delay, back of queue, effective stop rate and other ***traffic performance*** measures. Therefore model comparisons should not be restricted to discussion of capacity, and should consider complete framework of roundabout modelling. Further discussion of model comparison is outside the scope of this paper.

Differences between the AUSTROADS and aaSIDRA roundabout analysis methods are summarised in *Section 2*. Some important aspects of the analysis method where significant differences exist between the two methods are discussed in *Sections 3 to 8*.

2. aaSIDRA ENHANCEMENTS TO THE AUSTROADS (1993) METHOD

Those basic aspects of the aaSIDRA method for roundabout capacity estimation that are based on the AUSTROADS (1993) model are summarised in *Table 2.1*. Extensions and enhancements introduced in aaSIDRA (versions before aaSIDRA 2.1) are summarised in *Table 2.2* (Akçelik 1994, 1997; Akçelik and Chung 1994a,b; Akçelik, Chung and Besley 1996, 1997b, 1998). A summary of major refinements introduced to the roundabout capacity and performance models in the latest version aaSIDRA 2.1 are given in *Table 2.3* (Akcelik & Associates 2004).

The most important features of the AUSTROADS - aaSIDRA capacity estimation method, as summarised in *Table 2.1*, are the dependence of gap acceptance parameters on roundabout geometry, circulating flows and entry lane flows, and the designation of approach lanes as dominant and subdominant lanes that have different capacity characteristics.

The most important enhancement to the capacity estimation method introduced in aaSIDRA is allowance for the effects of *origin-destination pattern* of entry flows, amount of queuing on approach roads, and approach lane use. This contrasts with the traditional method of roundabout modelling that treats the roundabout as a series of independent *T-junctions* with no interactions among approach flows (except for the use of capacity constraint). While the traditional method as used in the AUSTROADS (1993) has been adequate for low to medium flow conditions, the interactive method used in aaSIDRA improves the prediction of capacities under heavy flow conditions, especially at *multi-lane roundabouts* with *unbalanced* demand flows.

As a result of numerous enhancements to the roundabout capacity and performance analysis introduced in aaSIDRA, significant differences exist between the aaSIDRA and AUSTROADS methods in spite of their common origin. The following important differences are discussed in *Sections 3 to 8*:

- capacity formulation using the saturation headway and proportion unblocked time parameters explicitly (*Section 3*);
- the Origin-Destination (O-D) factor that allows for the effects of O-D pattern, approach queuing and approach lane use, and is related to priority reversal and priority emphasis (*Section 4*);
- revised follow-up headway and critical gap models, and adjustment for heavy vehicles (*Section 5*);
- a revised function for proportion bunched and handling of extra bunching for upstream signal effects (*Section 6*);
- geometric delay determined using a detailed drive-cycle method and applied to queued and unqueued vehicles, not to queued vehicles only (*Section 7*); and
- roundabout model calibration parameters, namely Environment Factor and adjustment level for the arrival (demand) flow / circulation flow ratio (*Section 8*).

There are other important differences between the aaSIDRA and AUSTROADS methods (as seen in *Tables 2.2 and 2.3*) which are not discussed in this paper due to space limitation. Further information on the aaSIDRA capacity and performance models for roundabouts can be found in the aaSIDRA User Guide (Akcelik & Associates 2004).

Table 2.1

Main features of the aaSIDRA method for roundabout capacity estimation based on the AUSTROADS (1993) method

Gap acceptance parameters are related to roundabout geometry as well as circulation and entry flows:

- *Follow-up headway* decreases with:
  - increasing diameter of the roundabout,
  - increasing circulation flow,
  - decreasing number of circulation lanes, and
  - increasing number of entry lanes.
- *Critical gap* is proportional to the follow-up headway. The ratio of the critical gap to the follow-up headway is in the range 1.1 to 2.1, and decreases with increasing:
  - circulation flow **(1)**,
  - number of circulating lanes, and
  - average entry lane width.

  Thus, driver behaviour changes with roundabout geometry as well as increased circulation flows (more vehicles can depart through an acceptable gap, and shorter critical gaps are accepted).
  This confirms Kimber's (1989) observations.

  The enhancements introduced in aaSIDRA (see *Table 2.2*) makes the roundabout analysis method further differ from a simple gap acceptance analysis.
- For multi-lane approach roads, the lane with the largest flow rate is called *dominant lane* and the other lanes are called *subdominant lanes*:
  - the follow-up headway for traffic in a subdominant lane is greater than the follow-up headway for the dominant lane traffic, and
  - the ratio of follow-up headways for the subdominant and dominant lanes increases as the ratio of dominant lane flow to subdominant lane flow increases.

  Thus, entry lane capacities depend on entry flows, requiring an iterative method to estimate lane flows and capacities.
- Heavy vehicle effects are accounted for using a heavy vehicle equivalent **(2)**.

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(1) In aaSIDRA 2.1, a nonlinear critical gap - circulating flow relationship was introduced. See *Table 2.3*.

(2) In aaSIDRA 2.1, the heavy vehicle equivalent for gap acceptance models (for all intersection types) can be specified by the user to enable model calibration.

Table 2.2

Enhancements to roundabout analysis method introduced in various versions before aaSIDRA 2.1

- Consistency of capacity and performance models for roundabouts, other unsignalised intersections and signalised intersections is achieved through the use of an integrated modelling framework. For example back of queue and effective stop rate models use parameters derived from gap-acceptance methodology.
- Capacity formulation in aaSIDRA differs from the AUSTROADS method in using the saturation headway and proportion unblocked time parameters explicitly (similar to signalised intersection capacity formulation)
- Origin-Destination (O-D) pattern, approach queuing and approach lane usage affect entry lane capacities (roundabout is *not analysed as a series of independent T-junctions*). AUSTROADS method grossly overestimates capacities at high circulating flow rates. aaSIDRA corrects for this overestimation using *an O-D factor* which incorporates priority reversal and priority emphasis effects.
- *Capacity constraint* for oversaturated approaches is applied in determining circulating and exiting flow characteristics (only the capacity flow can enter the circulating road).
- An iterative method is used to calculate the circulating flow (for entry lanes) and the exiting flow (for slip lanes) for each approach, and for each circulating and exiting flow, determine the proportion of heavy vehicles, proportion of queued vehicles from the dominant approach and proportions of vehicles in single and multi-lane streams.
- Gap acceptance parameters (critical gap and follow-up headway) are adjusted for heavy entry flows against low circulating flows (the ratio of entry lane demand flow to the circulating flow). This parameter affects capacity at low circulating flow rates. The level of adjustment can be specified by the user to allow model calibration (see *Table 2.3*).
- Various limits (minimum and maximum values) are applied to the values of gap acceptance parameters.
- Different critical gap and follow-up headways can be specified by the user for different turns (left, through, right) from the same approach.
- A proportion of exiting flow can be added to the circulating flow.
- Intra-bunch headways and proportion bunched depend on effective lane use and lane flows in the circulating stream considering contributing approach streams.
- Extra bunching for upstream signal effects is specified by the user for approach roads. aaSIDRA calculates effective extra bunching for each circulating stream according to the extra bunching specified and proportion unqueued calculated for each contributing approach stream.
- Entry lane flows estimated as a function of lane capacities (iterative calculations are performed).
- Lane underutilisation for entry lanes: Unequal approach lane utilisation is allowed. e.g. for downstream destination effects.
- Short lane model applies through the use of back of queue formulation (*excess flow* is assigned to adjacent lanes when the average back of queue exceeds the available storage space in the short lane).
- Slip lanes are modelled by treating the exiting flow as the opposing stream.
- Detailed lane-by-lane and drive-cycle modelling of capacity and performance are applied (including fuel consumption, operating cost and pollutant emissions).
- Time-dependent performance formulae are used for application to oversaturated cases with continuity between undersaturated and oversaturated conditions.
- Performance estimates are given for delay (control delay, stop-line delay, stopped delay, geometric delay, etc), back of queue and cycle-average queue length (mean, 70^{th}, 85^{th}, 90^{th}, 95^{th}, 98^{th} percentile values), queue move-up rate, effective stop rate, proportion queued and so on.
- The geometric delay method is consistent for all intersection types. The aaSIDRA method differs from the AUSTROADS (1993) method in applying the geometric delays to queued and unqueued vehicles, and using a detailed drive-cycle method to determine geometric delays.
- A detailed method is used for determining negotiation radius, speed and distance for movements using a roundabout, allowing for path smoothing behaviour of drivers (Akçelik and Besley 2001).

Table 2.3

Enhancements to roundabout analysis method introduced in aaSIDRA version 2.1

Major refinements were introduced to the roundabout capacity and performance models in aaSIDRA 2.1. Some modelling changes apply to all unsignalised intersections, and also to gap-acceptance at signalised intersections. The following is a summary of these enhancements.

- Roundabout capacity model *calibration* parameters were introduced:
  - *Environment Factor* for the basic capacity model (capacity increases with decreasing Environment Factor; the value of this calibration parameter can be set in the Configuration facility),
  - adjustment level for the arrival (demand) flow / circulation flow ratio (the level of adjustment can be specified in the Configuration facility as High, Medium, Low, None),
  - the *Heavy Vehicle Equivalent for Gap Acceptance* parameter can be set in the Configuration facility (the method applies to all models including filter / permitted turns at signals).
- After further investigation of the original survey data (Troutbeck 1985):
  - follow-up headway model parameters were revised,
  - a nonlinear model for the critical gap parameter was introduced (this estimates small increases in critical gap values at very high circulating flow rates),
  - intra-bunch headway values for multi-lane circulating streams were changed from 1.2 s to 1.0 s for two-lane streams and from 1.0 s to 0.8 s for three lanes or more,
  - default values of the minimum follow-up headway and minimum critical gap were reduced from 1.2 s and 2.2 s to 1.0 s and 2.0 s, and the maximum value of follow-up headway was increased from 4.0 s to 5.0 s,
  - the minimum and maximum values of the inscribed diameter parameter used in the dominant lane follow-up headway equation were changed from 20 m and 80 m to 15 m and 250 m,
  - the upper limit of the minimum departures parameter for roundabouts and two-way sign-controlled intersections was increased to 10 veh/min.
- A new function was introduced for proportion bunched (using a parameter related to speed-flow functions).
- Follow-up headway and critical gap parameters are adjusted for heavy vehicles.
- A continuous heavy vehicle adjustment factor is applicable for all heavy vehicle proportions above zero per cent (model applies to all intersection types).
- A new function was introduced for the O-D flow pattern effect on capacity.
- A new effective unblocked time ratio parameter is used in performance functions.
- Dominant lane determination rule was changed.
- Priority sharing and priority emphasis issues were clarified.
- Circulating stream speed and spacing information were included in output tables.
- Maximum negotiation (design) speed parameter was introduced as a user default.
- For the negotiation speed model, a new side friction factor model as a function of speed was introduced, and superelevation default for negotiation speed was changed from 0 to -0.02 (this change applies to all intersection types).
- The new heavy vehicle factor and effective unblocked time ratio methods are applied to capacity and performance models for two-way sign control sign control as well (performance models are improved using this method due to better representation of the effects of adjustment factors for effects of heavy vehicles, the origin-destination flow pattern, and similar factors).

3. CAPACITY MODEL

In aaSIDRA, the basic equation for the calculation of capacity, which is applicable to both signalised and unsignalised intersections, is:

$$Q = s\,u \qquad (3.1)$$

where s = saturation flow rate (veh/h) and u = green time ratio (signalised intersections) or *unblocked time ratio* (unsignalised intersections).

For any gap-acceptance process, the saturation flow rate is

$$s = 3600 / \beta \qquad (3.1a)$$

where β is follow-up headway of the entry stream (seconds), and the unblocked time ratio is u = g / c, where g = average unblocked time (seconds) and c = average gap-acceptance cycle time (seconds).

The follow-up headway is the saturation headway, i.e. the minimum headway between vehicles that is achieved while they are departing from the queue. For example, β = 2.5 seconds implies a saturation flow rate of s = 1440 veh/h. This is the maximum capacity that can be achieved when the opposing flow is close to zero. The capacity is reduced from this value with increased opposing flow rates due to decreased unblocked time ratio (u).

All roundabout capacity models predict decreased capacity with increased circulating flow. In terms of general gap-acceptance modelling, this is due to the *blocked periods* that result when the approach vehicles cannot find an acceptable gap in the circulating stream. *Unblocked periods* represent the times a gap is available in the circulating flow and queued or unqueued vehicles can enter the circulating road. Blocked and unblocked periods are like *effective red and green times* at signals (Akçelik 1994).

Many different forms of the gap-acceptance capacity formula that exist, including the US HCM (TRB 2000) and the AUSTROADS (1993) capacity equations, can be explained in terms of the gap-acceptance capacity concept expressed by *Equation (3.1)*.

For roundabouts, aaSIDRA estimates the unblocked time ratio for use in *Equation (3.1)* from:

$$u = \mathit{max}\,\{u_{min},\ f_{od}\,(1 - \Delta_c\,q_c + 0.5\,\beta\,\varphi_c\,q_c)\,e^{-\lambda(\alpha-\Delta_c)}\} \qquad (3.2)$$

$$u_{min} = Q_m / s \qquad (3.3)$$

$$\lambda = \varphi_c\,q_c / (1 - \Delta_c\,q_c) \qquad \textit{subject to } q_c \le 0.98 / \Delta_c \qquad (3.4)$$

where u_{min} is the minimum value of the unblocked time ratio, f_{od} is the Origin-Destination (O-D) factor (see *Section 4*), Q_m is the minimum capacity per lane (veh/h), s is the saturation flow rate (veh/h), β is the follow-up headway (seconds) and α is the critical gap (seconds) for the entering stream (see *Section 5*), Δ_c is the intrabunch headway (seconds) and φ_c is the proportion unbunched for the circulating stream (see *Section 6*), and q_c is the circulating flow rate (pcu/s).

It is seen that, in addition to the circulating flow rate, the follow-up and critical gap parameters representing the behaviour of drivers in roundabout entry lanes, the bunching characteristics that affect the distribution of headways of vehicles in the circulating road, and the O-D factor that represent the pattern of demand flows are important factors that influence capacity and performance characteristics of roundabouts. These are discussed in *Sections 4 to 6*.

4. ORIGIN-DESTINATION (O-D) FACTOR

A unique feature of the aaSIDRA method for roundabout capacity estimation is to allow for the effects of the origin-destination pattern and approach queuing characteristics of traffic that constitute the circulating stream. For this purpose, an *Origin-Destination (O-D) factor* is used to effectively modify the distribution of circulating (opposing) stream headways.

The O-D factor was first introduced in an earlier version SIDRA to allow for unbalanced flow effects after research was conducted following reports received from many practitioners that overoptimistic results were obtained using the AUSTROADS Roundabout Guide (1993). It was found that the AUSTROADS method grossly overestimated capacities at high circulating flow rates especially with unbalanced flow patterns. The O-D factor was introduced to correct this overestimation (Akçelik, Chung and Besley 1996, 1997b, 1998).

While AUSTROADS (1993, Section 3.2) recognises that roundabouts operate better when the traffic flows are balanced, the capacity analysis method given in the guide does not account for the effect of flow balance. Thus, the O-D factor method represents a substantial change to the method described in the Australian Roundabout Guide from which aaSIDRA originated.

Figure 4.1 shows the comparison of capacity estimates from the AUSTROADS (1993) and old NAASRA (1986) methods, the UK linear regression model, and aaSIDRA 2.1 (two different flow patterns) for a two-lane roundabout example. It is seen that there is a very large difference between the AUSTROADS method and all other methods including the old NAASRA method for circulating flow rates above about 1200 veh/h. It is also seen that aaSIDRA can produce different capacity estimates according to the demand flow pattern, and the aaSIDRA capacity estimates get closer to the old NAASRA model estimates with higher O-D pattern effect.

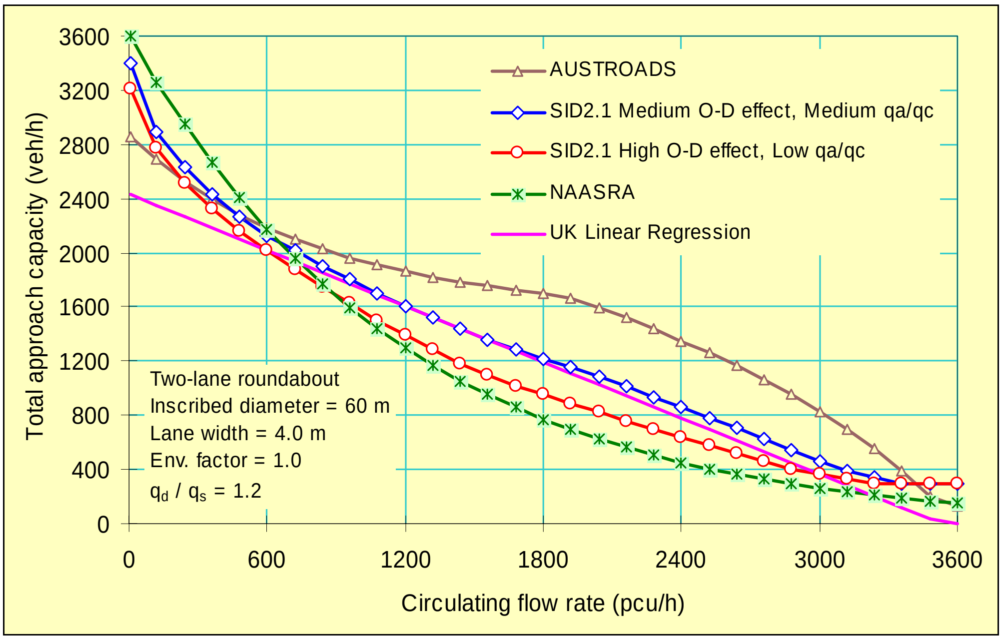

Figure 4.1 - Comparison of capacity estimates from the AUSTROADS and old NAASRA methods, the UK linear regression model, and aaSIDRA 2.1 (two different flow patterns) for a two-lane roundabout example

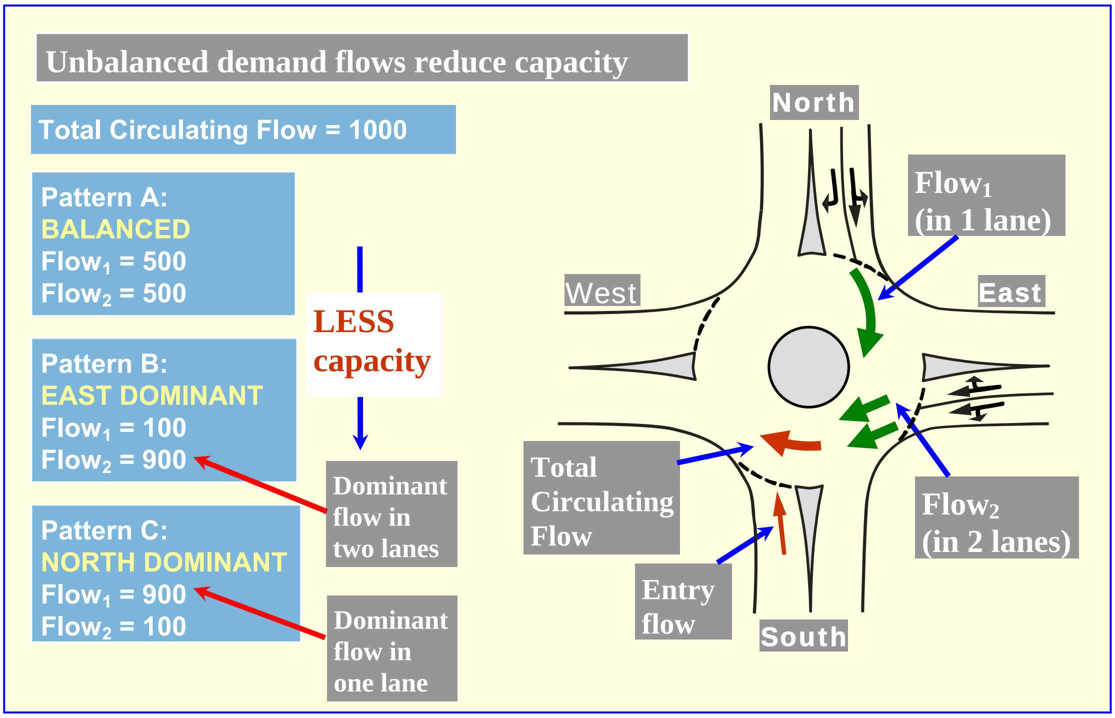

Figure 4.2 - The effect of the Origin-Destination (O-D) pattern on capacity

Figure 4.2 explains the effect of the O-D factor in aaSIDRA. It can be seen that different capacities and levels of performance may be estimated for the same circulating flow rate depending on the conditions of the component streams. The lowest capacity is obtained when the component stream flow rates are unbalanced and the main (dominant) stream is a very large proportion of the total circulating flow, it is in a single lane, and is highly queued on the approach lane it originates from. Thus, the O-D factor method takes roundabout analysis beyond the treatment of entry points as *a series of independent T-junctions*.

While traditional methods may be adequate for low flow conditions, the O-D factor improves the prediction of capacities under medium to heavy circulating flow conditions, especially with *unbalanced* demand flows where *priority emphasis* occurs. This helps to avoid capacity overestimation under such conditions as observed at many real-life intersections, which has been a concern expressed by many practitioners. In many real-life cases considered (see articles by Akçelik 2003a, 2004), the methods without the unbalanced flow modelling (including the AUSTROADS 1993, US HCM and UK linear regression models) predict good operating conditions whereas long delays and queues are observed on one or more approaches of these roundabouts.

The effect of the O-D factor is to reduce the capacity especially in the case of heavy circulating (or existing) flow conditions with unbalanced flow patterns. The amount of reduction in capacity increases as the proportion of the total circulating stream flow that originated from and were queued on the *dominant approach* increases. The dominant approach is determined as the approach that contributes the highest proportion of the queued traffic in the circulating flow. If the O-D factor is close to 1.0, there is negligible effect. If it is about 0.5, the effect is very large.

The application of the O-D factor to the unblocked time ratio in aaSIDRA 2.1 introduces another significant change to the model due to the direct use of this parameter in performance equations (previously applied to the capacity value). The entry capacity resulting from applying the O-D factor to the *unblocked time ratio* (modifying the circulating stream headway distribution model) is the same as the capacity obtained when the O-D factor is applied directly to the capacity derived from the theoretical gap-acceptance model. However, the method introduced in aaSIDRA 2.1 (*Equation 3.2*) has the advantage of better modelling of roundabout performance (delay, queue length, effective stop rate, etc) using the effective gap-acceptance cycle time, unblocked time and blocked time parameters modified to allow for the effect of the O-D pattern and queuing.

Figures 4.3 and 4.4 show the unblocked time ratio and capacity for three levels of O-D flow pattern effect, namely *Low* O-D pattern effect (balanced flows and low level of queuing), *Medium* O-D pattern effect (less balanced flows and moderate level of queuing), and *High* O-D pattern effect (unbalanced flows and high level of queuing), as well as the capacity values without the O-D factor (f_{od} = 1.0). These figures are for the dominant lane of a two-lane roundabout (inscribed diameter = 50 m, average entry lane width = 4.0 m, Environment Factor = 1.0, Medium adjustment level for the ratio of entry flow to circulating flow, entry flow rate = 900 veh/h).

Priority Sharing and Priority Emphasis

The limited-priority method of gap-acceptance modelling described by Troutbeck and Kako (1997) and Troutbeck (1989, 1999, 2002) allows for ***priority sharing*** (priority reversal) between entering and circulating vehicles in order to introduce a correction to the gap-acceptance capacity formula based on *absolute priority* of circulating stream vehicles. The need for adjustment is due to low critical gap values at high circulating flow rates which may result in the condition $\beta + \Delta > \alpha$, where β = follow-up headway, α = critical gap (headway) and Δ = intra-bunch headway. The limited-priority method ***reduces*** the capacity estimated by the absolute-priority method.

The Origin-Destination (O-D) factor used in the aaSIDRA roundabout capacity model incorporates the effect of priority sharing that results from very low critical gap values obtained under high circulating flow rates at roundabouts. Furthermore, the non-linear relationship between the critical gap and circulating flow rate used in aaSIDRA version 2.1 (see *Section 5*) reduces the amount of adjustment to the capacity function based on absolute priority since it estimates larger critical gap values at high circulating flows, unlike the linear model used in AUSTROADS (1993).

Without the O-D factor (or any other method that allows for priority sharing), the gap-acceptance capacity formula (based on absolute priority) gives unduly high capacity estimates at medium to high circulating flow rates, especially for multilane roundabouts (as seen for the AUSTROADS method in *Figure 4.1*). The method used in aaSIDRA to incorporate the O-D factor into the gap-acceptance formula is similar to the method to adjust for the limited-priority gap-acceptance process described by Troutbeck and Kako (1997) and Troutbeck (1999, 2002). However, the process can be one of ***priority emphasis*** (opposite of priority reversal) in the case of unbalanced flow patterns as allowed for in aaSIDRA (Akçelik 2004).

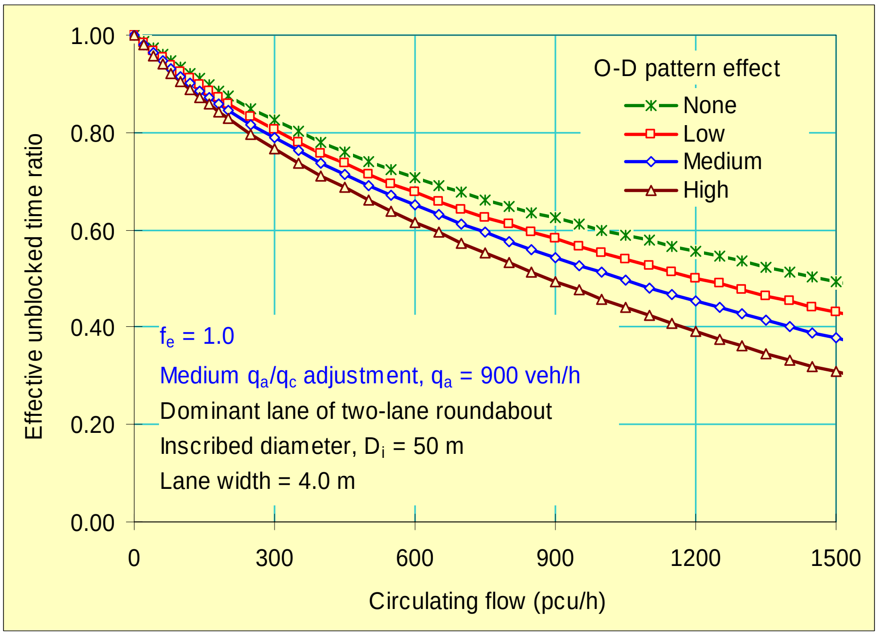

Figure 4.3 - Effective unblocked time ratio as a function of circulating flow for three levels of O-D flow pattern effect and without the O-D pattern factor for the dominant lane of a two-lane roundabout

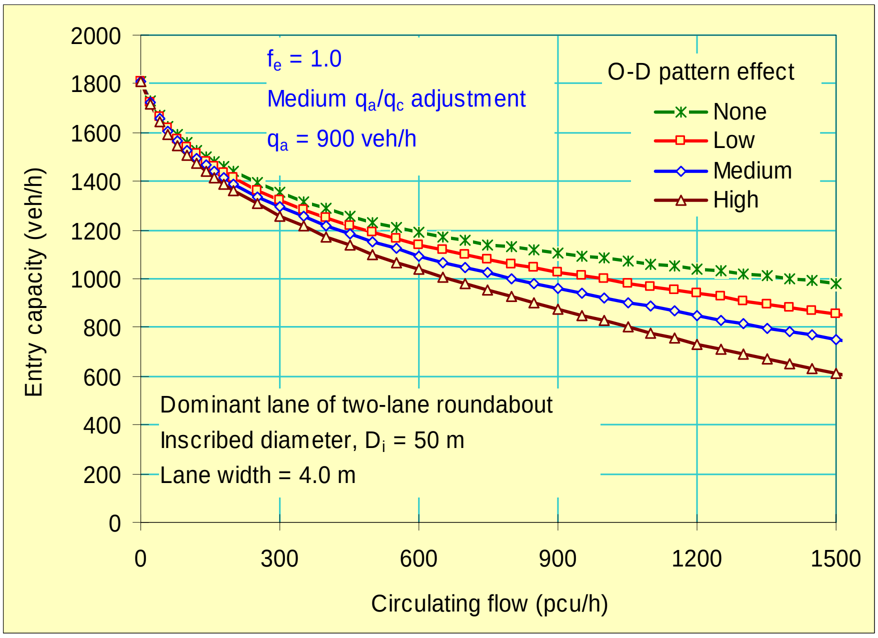

Figure 4.4 - Entry lane capacity as a function of circulating flow for three levels of O-D flow pattern effect and without the O-D pattern factor for the dominant lane of a two-lane roundabout

The O-D factor in aaSIDRA allows for the fact that vehicles entering from the approach queues are under *forced flow* conditions, and as such they are considered to be *bunched*. Without the O-D factor that reduces the unblock time ratio (in effect, modifying the circulating stream headway distribution model), the gap-acceptance capacity formula gives unduly high capacity estimates at medium to high circulating flow rates, especially for multilane roundabouts. While the O-D factor allows for capacity reduction needed to model priority sharing, it also allows for reduced unblock time due to an opposite effect, which can be called *priority emphasis.*

The *priority emphasis* condition occurs in the case of unbalanced flow patterns when a dominant flow restricts the amount of entering traffic since most vehicles in the circulating stream have entered from a queue at the upstream approach continuously due to a low circulating flow rate against them (see *Figure 4.5*). Even a small amount of circulating flow can cause a significant proportion of vehicles to be queued on an approach with a heavy flow rate, although the capacity can be high. This also corresponds to the case of long back of queue and low delay.

Of particular concern is the application of the bunched exponential model of headway distribution to roundabout circulating streams without due attention to the headways of vehicles entering from approach queues, i.e. entering with follow-up (saturation) headway. Roundabout circulating streams are *uninterrupted* flows in short road segments on the circulating road (between *entry - circulating road junctions*), and they contain *queued vehicles* entering from approach lanes. Vehicles departing from a queue with follow-up headways are in forced flow conditions, and should be considered to be bunched when negotiating the roundabout even though the follow-up headway is longer than the intrabunch headway used in the general bunching model which is based on average circulating flow conditions.

Figure 4.5 - An example of dominant entry flow at a roundabout (Melbourne, Australia)

A heavy stream that can enter the roundabout with little interruption due to a low circulating flow rate against it (*unbalanced flow* conditions) represents mainly forced flow conditions (with follow-up headways that can be larger than the intrabunch headway), and cause reduced capacity at a downstream entry. The *origin-destination factor* in aaSIDRA takes into account the flow balance as well as the amount of queuing in the circulating stream, in effect modifying the circulating stream headway distribution to allow for these factors.

Without allowance for *priority emphasis*, the AUSTROADS (1993) method, or any method based on gap-acceptance modelling or regression ("empirical") method with or without *priority sharing*, fails to provide satisfactory estimates of roundabout capacity with unbalanced flows (see the case studies given in Akçelik 2003a, 2004).

5. FOLLOW-UP HEADWAY AND CRITICAL GAP

Follow-up Headway

aaSIDRA uses a linear regression equation for calculating the ***follow-up headway*** (β), subject to a minimum follow-up headway value. The equation is based on data observed at Australian roundabouts (see *Section 1*). The model was revised in aaSIDRA version 2.1 using the survey data and an *Environment Factor* was added for calibration purposes (see *Section 8*). The follow-up headway values estimated by the aaSIDRA formula are now about 5 per cent lower than the AUSTROADS (1993) formula.

In both the AUSTROADS and aaSIDRA methods, gap-acceptance parameters depend on approach lane characteristics identified as dominant lane (higher lane volume, lower follow-up headway and critical gap values) and subdominant lane (lower lane volume, higher follow-up headway and critical gap values). A detailed procedure is specified in aaSIDRA in order to determine the dominant lane for each roundabout approach.

Parameters representing the *roundabout geometry* in the regression model for estimating the follow-up headway are the *inscribed diameter* (D_i), *number of entry lanes* (n_e), and *number of circulating lanes* (n_c).

The roundabout geometry parameters and the *Environment Factor* determine the follow-up headway at zero circulating flow. This value is reduced as a function of the circulating flow rate. Further adjustments are applied to the basic follow-up headway value for the ratio of entry (demand) flow rate to circulating flow rate and heavy vehicles.

Figure 5.1 shows the unadjusted dominant lane follow-up headway as a function of the circulating flow for three roundabout cases (observed values are also shown): 1-lane roundabout ($n_e = n_c = 1$) with D_i = 30 m, 2-lane roundabout ($n_e = n_c = 2$) with D_i = 50 m and 3-lane roundabout ($n_e = n_c = 3$) with D_i = 80 m (entry lane width = 4.0 m for all cases).

It is seen that the dominant lane follow-up headway decreases with increasing roundabout size (diameter and number of lanes) and increasing circulating flow rate. For a given circulating flow rate, decreased follow-up headway implies increased capacity. However, capacity is expected to decrease with increasing circulating flow rate in spite of decreased follow-up headway.

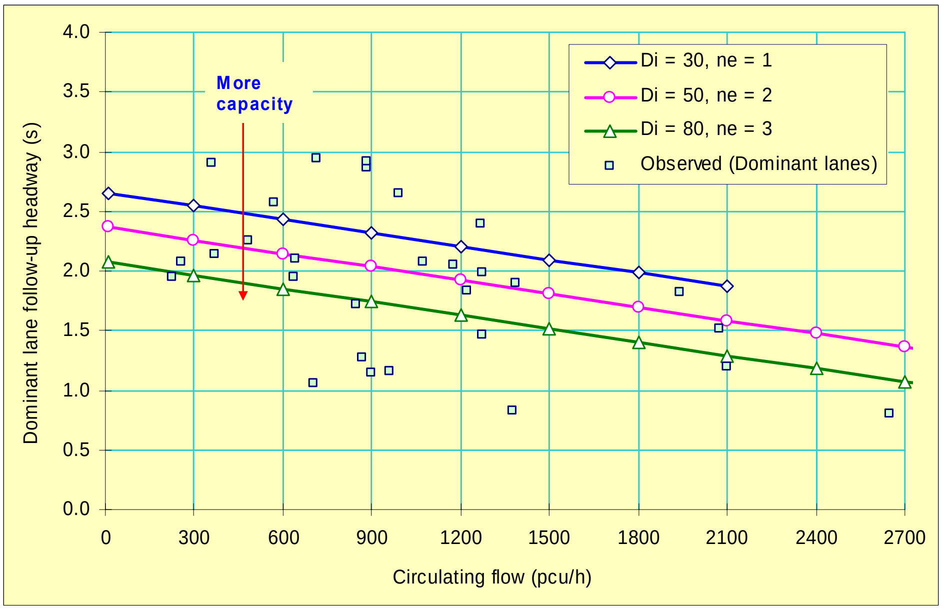

Figure 5.1 - Unadjusted dominant lane follow-up headway (β_{d1}) as a function of the circulating flow for three roundabout cases: 1-lane roundabout with D_i = 30 m, 2-lane roundabout with D_i = 50 m and 3-lane roundabout with D_i = 80 m (lane width = 4.0 m)

Critical Gap (Headway)

aaSIDRA uses a ***non-linear*** regression model for estimating the critical gaps at roundabouts. The equation is based on data observed at Australian roundabouts (see *Section 1*). The model was introduced in aaSIDRA version 2.1 to replace the linear model used in AUSTROADS (1993).

The critical gap is estimated as a function of the follow-up headway (dominant or subdominant lane value as relevant), circulating flow rate and various parameters representing the roundabout geometry, namely the *average entry lane width* (w_L) and *number of circulating lanes* (n_c). The roundabout geometry parameters *inscribed diameter* (D_i) and *number of entry lanes* (n_e) also affect the critical gap value through the follow-up headway parameter used in the model. The ratio of the critical gap to follow-up headway (α/β) is the same for dominant and subdominant lanes.

The adjustments for the environment factor, ratio of entry (demand) flow rate to circulating flow rate and heavy vehicles affect the critical gap through the follow-up headway parameter used in the model. The heavy vehicle factor applies to the follow-up headway and the critical gap in the same way since the model used for estimating critical gap is essentially a model for the ratio of critical gap to follow-up headway (α/β). The critical gap may differ for each movement in the lane if the HV percentages are different as in the case of follow-up headway values.

Figure 5.2 shows the critical gap corresponding to the unadjusted dominant lane follow-up headway as a function of the circulating flow for three roundabout cases as in *Figure 5.1* (observed values are also shown). It is seen that the dominant lane critical gap decreases with increasing roundabout size (diameter and number of lanes) and increasing circulating flow rate. The change in the slope of the critical gap function for the three-lane case occurs at the point when the critical gap is set equal to the minimum value (2.0 s).

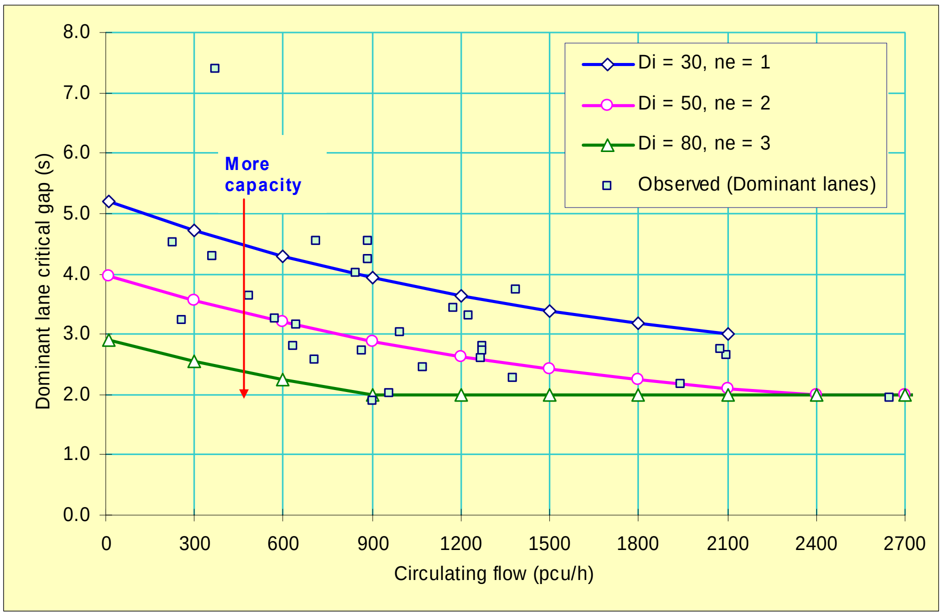

Figure 5.2 - Dominant lane critical gap corresponding to the unadjusted dominant lane follow-up headway as a function of the circulating flow for three roundabout cases: 1-lane roundabout with D_i = 30 m, 2-lane roundabout with D_i = 50 m and 3-lane roundabout with D_i = 80 m (average entry lane width = 4.0 m)

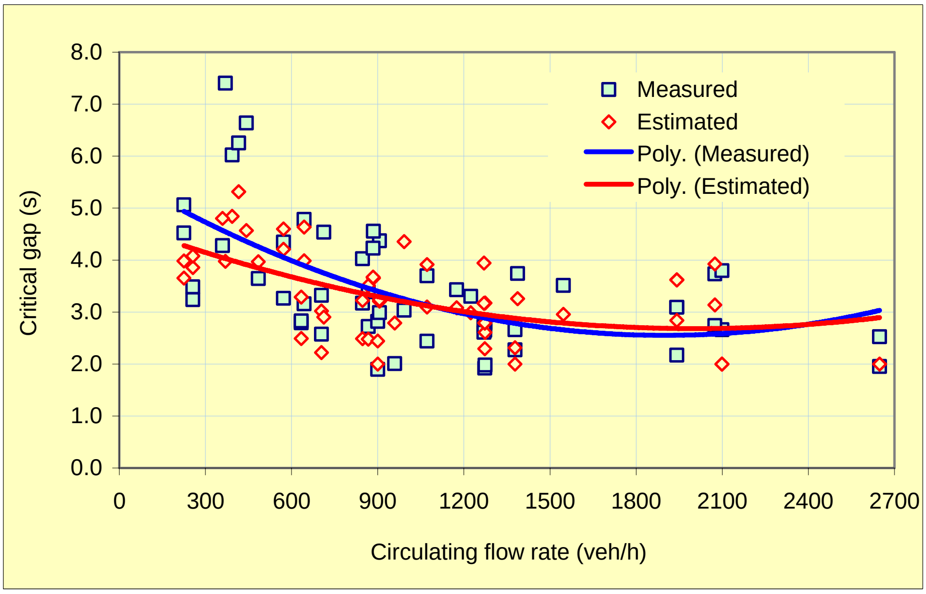

Figure 5.3 - Critical gaps observed at Australian roundabouts compared with estimates from the aaSIDRA critical gap model (non-linear trendlines shown)

The critical gap value decreases with the circulating flow rate for low to medium circulating flow rates, becomes fairly constant at high circulating flow rates, and starts increasing slightly at very high circulating flow rates. This feature of the non-linear model was found to represent observed critical values better as seen in *Figure 5.3*. This implies that it becomes more difficult to accept gaps at very high circulating flow rates although any acceptable gap is used more efficiently (in *Figure 5.1*, the follow-up headway is seen to decrease at high circulating flow rates subject to a minimum value).

Heavy Vehicles

aaSIDRA gap-acceptance models allow for the effect of heavy vehicles on the capacity of an opposed traffic stream by using a *heavy vehicle equivalent for gap acceptance*. This parameter represents the passenger car equivalent of a heavy vehicle for the purposes of gap-acceptance capacity estimation (this parameter can be specified by the user in aaSIDRA 2.1). It is used to calculate a *heavy vehicle factor* according to the proportion of heavy vehicles in the traffic stream.

The *heavy vehicle factor* is used to adjust (increase) the follow-up headway and critical gap parameters for heavy vehicles in the entry stream, and adjust (increase) the opposing / circulating stream volume to a pcu/h value for heavy vehicles in the opposing / circulating stream. The effect of these adjustments is to decrease the entry stream capacity. This method applies to modelling entry streams at roundabouts, minor streams at two-way sign control, all-way stop sign control as well as filter (permitted) turns at traffic signals. The method used before aaSIDRA 2.1 applied an *incremental* adjustment for heavy vehicle flows above 5 per cent as in AUSTROADS (1993). In aaSIDRA 2.1, a *continuous* function is used for the heavy vehicle factor which is applicable for all heavy vehicle proportions above zero per cent.

6. BUNCHING

In aaSIDRA and AUSTROADS (1993), the intra-bunch headway (Δ_c) and proportion of free (unbunched) vehicles (φ_c) are parameters used in the bunched exponential model used in aaSIDRA for estimating circulating stream headway distribution (see *Figure 6.1*).

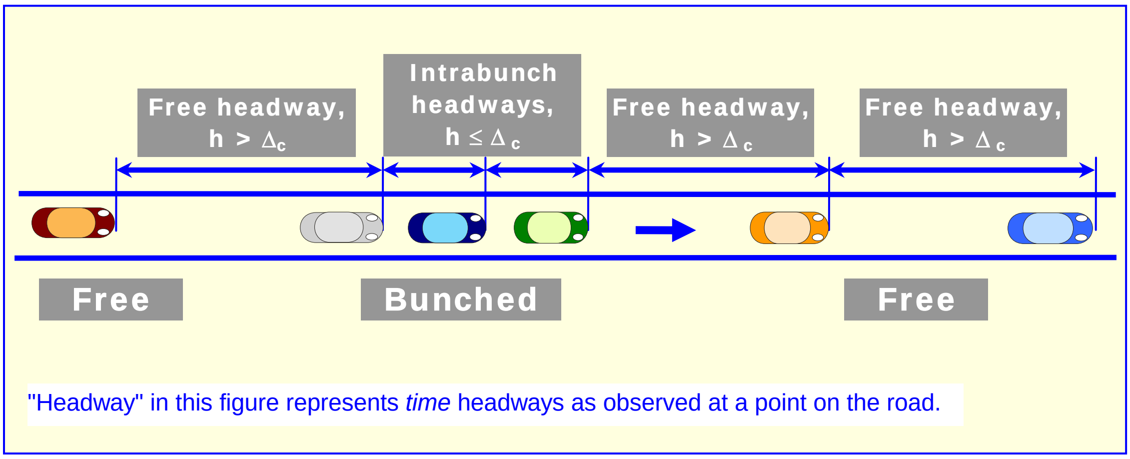

Figure 6.1 - Circulating stream parameters used in the bunched exponential model for estimating circulating stream headway distribution

The intra-bunch headway is the minimum headway in the arrival headway distribution model, and is the headway within each bunch (assumed to be equal for all vehicles in the bunch, and equal for all bunches). The proportion of free vehicles represents the unbunched vehicles with randomly distributed headways. Intra-bunch headway and proportion of unbunched vehicles are interdependent, i.e. the value of proportion unbunched depends on the selected value of the intra-bunch headway.

In aaSIDRA, the circulating (or exiting) stream is qualified as a *single-lane* or *multilane stream* according to the *effective use* of circulating (or exiting) lanes for the purpose of capacity and performance models. The values of parameters Δ_c and φ_c differ accordingly.

The intra-bunch headways for roundabout circulating streams are:

$$\begin{aligned} \Delta_c &= 2.0 \text{ s} \quad \textit{for single-lane circulating flow} \\ &= 1.0 \text{ s} \quad \textit{for two-lane circulating flow} \\ &= 0.8 \text{ s} \quad \textit{for circulating flow with more than two lanes} \end{aligned} \qquad (6.1)$$

The above values for multi-lane cases assume equal lane flows, and adjustment is made for unequal lane flows. For multi-lane circulating roads, aaSIDRA determines the circulating stream as single-lane, two-lane or other multilane by inspecting the *effective approach lane use* of the origin-destination streams that constitute the circulating stream. For example, the circulating stream in the case shown in *Figure 4.1* has a single-lane and a two-lane component. Where several origin-destination streams differ in being single-lane, two-lane or other multilane, the intra-bunch headway (Δ_c) for a subject circulating stream is calculated as a *flow-weighted average* of Δ_c values of the streams contributing to the circulating flow. The AUSTROADS (1993) method uses Δ_c = 1.0 s for all multi-lane circulating streams irrespective of lane use of contributing streams.

For roundabouts, aaSIDRA estimates the proportion of free (unbunched) vehicles in the circulating (or exiting) stream (φ_c) from:

$$\varphi_c = (1 - \Delta_c\, q_c) / [1 - (1 - k_d)\, \Delta_c\, q_c] - \delta\varphi_c \quad \textit{subject to } \varphi_c \geq 0.001 \qquad (6.2)$$

where q_c is the circulating (or exiting) flow rate (pcu/s), Δ_c is the average intra-bunch headway (s), k_d is the bunching delay parameter (a constant), and $\delta\varphi_c$ is the average effective extra bunching *calculated by aaSIDRA* for the subject circulating flow.

In versions before aaSIDRA 2.1, the following exponential model was used for the prediction of proportion free (unbunched) vehicles:

$$\varphi_c = e^{-b\, \Delta_c\, q_c} \qquad (6.3)$$

where b is a constant, Δ_c and q_c are as in *Equation (6.1)*.

The model introduced in aaSIDRA 2.1 *Equation (6.1)* was developed by considering a fundamental relationship between travel delay parameter in Akçelik's speed-flow function and the bunching delay obtained through the bunching model to determine vehicle headway distributions for uninterrupted movements (Akçelik 2003b). Parameter k_d in *Equation (6.1)* is the delay parameter in Akçelik's speed-flow function. The average intra-bunch headway is treated as the average headway at capacity (Δ_c = 3600 / Q where Q is the capacity in veh/h).

AUSTROADS (1993) uses the following linear model:

$$\varphi_c = 0.75\, (1 - \Delta_c\, q_c) \qquad (6.4)$$

Figures 6.2 and 6.3 show the proportion unbunched (measured and estimated by alternative models) for single-lane and two-lane circulating streams at roundabouts together with the Australian roundabout survey data. It is seen that, compared with the AUSTROADS linear model for roundabouts, the values of φ estimated by *Equation (6.1)* are higher for low circulating flows (less bunched) and lower for high circulating flows (more bunched).

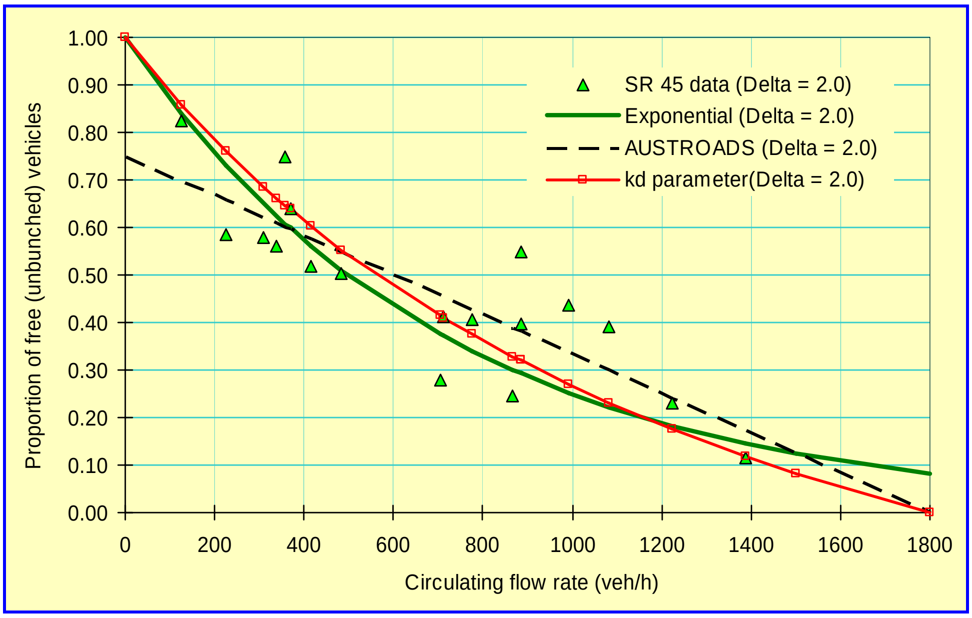

Figure 6.2 - Proportion unbunched for single-lane circulating streams at roundabouts as a function of the circulating flow rate (measured and estimated by alternative bunching models)

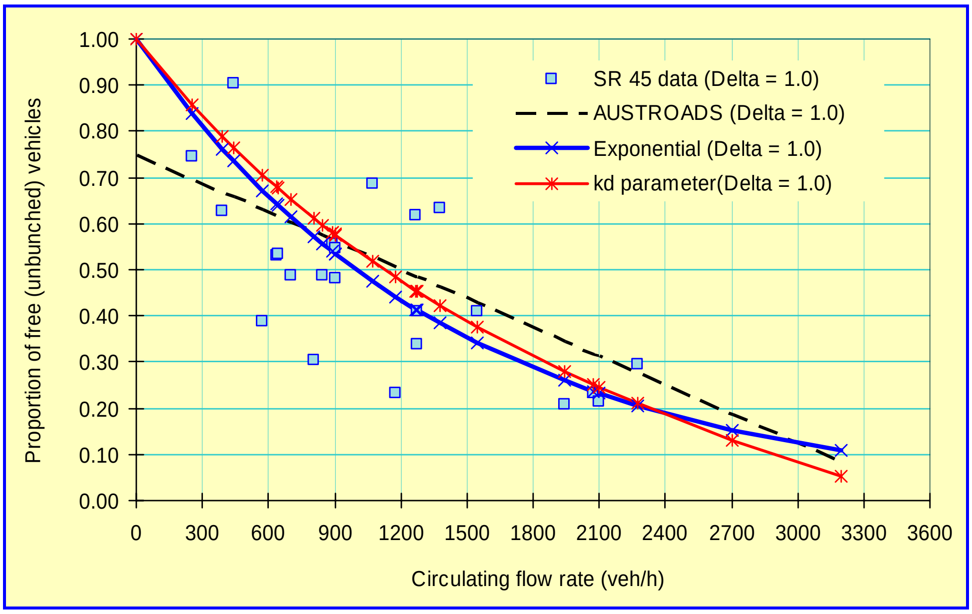

Figure 6.3 - Proportion unbunched for two-lane circulating streams at roundabouts as a function of the circulating flow rate (measured and estimated by alternative bunching models)

Extra Bunching

Another significant difference between the aaSIDRA and AUSTROADS (1993) methods is in specifying and applying the ***extra bunching*** parameter. This parameter is used to adjust the proportion of free vehicles according to the proximity of an upstream signalised intersection. This applies when the upstream signals are too close or too far from the roundabout give-way line.

Using the extra bunching data specified by the user for each approach, aaSIDRA determines *effective extra bunching* ($\delta\varphi_c$ in *Equation 6.2*) for each *circulating stream* according to different components of that circulating stream in terms of the contributing approach streams (flow-weighted average is used). This method considers that extra bunching for the effect of upstream signals applies to the demand flow arriving at the back of the queue on the subject approach, and the amount of bunching is filtered through the queuing processes at contributing roundabout approaches. Generally, the extra bunching value for a circulating stream is expected to be much less than the values specified for contributing approach roads. As such, the aaSIDRA method differs from the method given in the AUSTROADS (1993) roundabout guide, which specifies extra bunching directly for the circulating stream in front of the approach.

7. GEOMETRIC DELAY

Geometric delay is the delay experienced by a vehicle going through (negotiating) the intersection in the absence of any other vehicles (see *Figure 7.1*). Geometric delay is due to a deceleration from the approach cruise speed down to a *safe approach negotiation speed*, travelling at that speed, acceleration (or deceleration) to an exit negotiation speed, travelling the rest of exit negotiation distance at constant exit negotiation speed and then acceleration to the exit cruise speed.

The delay to a vehicle which decelerates from the approach cruise speed to a *full stop* (due to a reason such as a red signal, a queue ahead, or lack of an acceptable gap), waits and then accelerates to the exit cruise speed is considered to include the delay due to a deceleration from the approach cruise speed down to an approach negotiation speed and then to zero speed, idling time, acceleration to an exit negotiation speed along the negotiation distance, travelling the rest of the negotiation distance (if any) at the constant exit negotiation speed, and then acceleration to the exit cruise speed. As seen in *Figure 7.1*, this delay is the ***control delay***. This is sum of *stop-line* and *geometric* delays, and includes all deceleration and acceleration delays experienced in negotiating the intersection.

The stop-line delay is calculated by projecting the time-distance trajectory of a queued vehicle from the approach and exit *negotiation* speeds to the stop line (or give-way / yield line), which is shown as the time from C to F in *Figure 7.1*.

A key construct used in developing the aaSIDRA delay definitions given above is a clarification of whether the delay estimated by a traditional analytical delay model includes any acceleration and deceleration delays. The basic premise of aaSIDRA is that the analytical model delay is a *stop-line delay* that includes the *main stop-start delay* to queued vehicles (sum of times C to D and E to F in *Figure 7.1*), and does not include the *geometric delay*. The stop-line delay includes *stopped delay* (idling time at zero speed) (D to E in *Figure 7.1*)

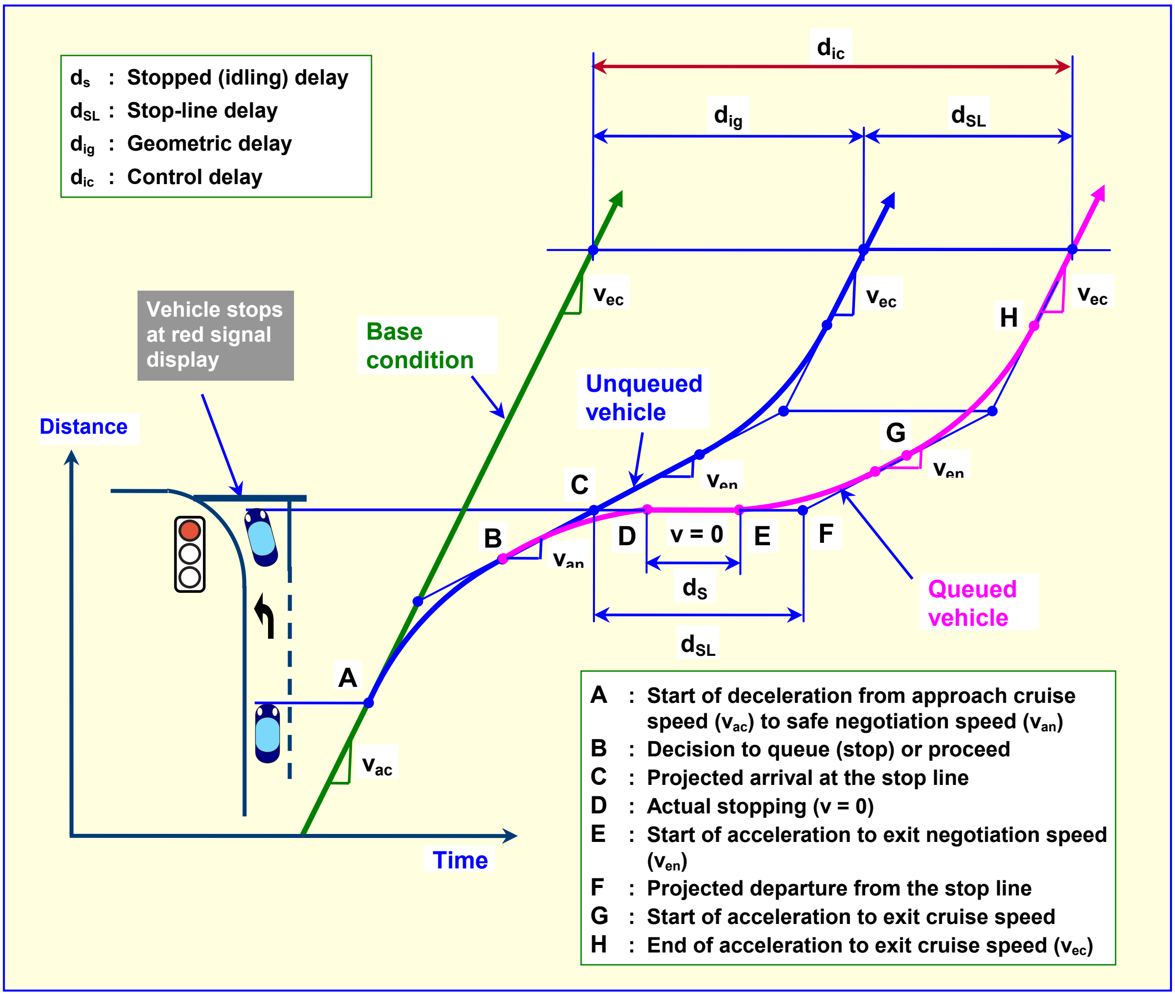

Figure 7.1 - Definition of control delay, geometric delay, stop-line delay, and stopped delay experienced by a turning vehicle at an intersection (case when the approach and exit cruise speeds are the same, $v_{ac} = v_{ec}$, and the approach and exit negotiation speeds are the same, $v_{an} = v_{en}$)

Thus, every vehicle in a given stream experiences the same geometric delay which is associated with safe approach and exit *negotiation* speeds through the intersection. As such, the method used in aaSIDRA differs from the AUSTROADS (1993) method that calculates separate geometric delay values for queued and unqueued (stopped and unstopped) vehicles. The AUSTROADS method assumes that the analytical model delay does not include any deceleration and acceleration delays.

aaSIDRA uses a detailed drive-cycle model for determining the geometric delay for each intersection type as a function of the intersection geometry, control type and approach, negotiation and exit speeds. The aaSIDRA method for determining the negotiation speeds at roundabouts, and the acceleration and deceleration models used in aaSIDRA are described in Akçelik (2002) and Akçelik and Besley (2001).

8. MODEL CALIBRATION

The aaSIDRA roundabout capacity model can be calibrated to reflect local road and driver characteristics and particular intersection conditions if necessary. This can be achieved using the *Environment Factor* and *Adjustment Level for Arrival Flow / Circulation Flow Ratio* parameters. These parameters affect the follow-up headway and critical gap (therefore capacity) values of all lanes at a roundabout.

Environment Factor

The Environment Factor can be used to calibrate the capacity model to allow for less restricted (higher capacity) and more restricted (lower capacity) roundabout environments. This factor represents the general roundabout environment in terms of roundabout design type, visibility, significant grades, operating speeds, size of light and heavy vehicles, driver aggressiveness and alertness (driver response times), pedestrians, heavy vehicle activity (goods vehicles, buses or trams stopping on approach roads), parking turnover and similar factors affecting vehicle movements on approach and exit sides as well as the circulating road as relevant. These should be taken into account in terms of their impact on vehicles entering the roundabout.

Higher capacity conditions could be a result of factors such as good visibility, more aggressive and alert driver attitudes (smaller response times), negligible pedestrian volumes, and insignificant parking and heavy vehicle activity (goods vehicles, buses, trams stopping on approach roads).

Lower capacity (more restricted) conditions could be a result of factors such as compact roundabout design (perpendicular entries), low visibility, relaxed driver attitudes (slower response times), high pedestrian volumes, and significant parking and heavy vehicle activity (goods vehicles, buses, trams stopping on approach roads).

The default value of the Environment Factor is 1.0. This factor adjusts the dominant lane follow-up headway at zero circulating flow. As a result, the dominant lane follow-up headway values at all circulating flows are adjusted. This leads to the adjustment of subdominant lane follow-up headway, as well as adjustments of critical gaps for all lanes. Capacity increases with decreasing value of the Environment Factor, e.g. 0.95 will give higher capacities compared with the default value of 1.0, while 1.05 will give lower capacities (see *Figure 8.1*).

Adjustment Level for Arrival Flow / Circulation Flow Ratio

In order to avoid underestimation of capacities at low circulating flows, aaSIDRA decreases the dominant lane follow-up headway as a function of the ratio of arrival (entry lane) flow to circulating flow. As with the Environment Factor, the adjustment (reduction) of the dominant lane follow-up headway results in reduction of the subdominant lane follow-up headway as well as the critical gap values for both dominant and subdominant lanes. As a result capacities are increased for all entry lanes.

The user can calibrate the roundabout capacity model by choosing the level of this adjustment according to the observed or expected local driver behaviour characteristics (level of adjustment can be High, Medium, Low and None). The selected level determines the adjusted dominant lane follow-up headway at zero circulating flow. The adjustment (decrease in follow-up headways and critical gaps, therefore increase in capacity) is effective for low to medium circulating flow rates. Capacity is highest when High is selected, and lowest when None is selected (see *Figure 8.1*).

In addition to the *Environment Factor* and *Adjustment Level for Arrival Flow / Circulation Flow Ratio* parameters, a *Heavy Vehicle Equivalent for Gap Acceptance* parameter can be used to model the effect of heavy vehicles on the capacity of traffic streams subject to gap-acceptance process (see *Section 5*), and the *Maximum Negotiation (Design) Speed* parameter can be used for calibrating the aaSIDRA negotiation speed model for roundabouts.

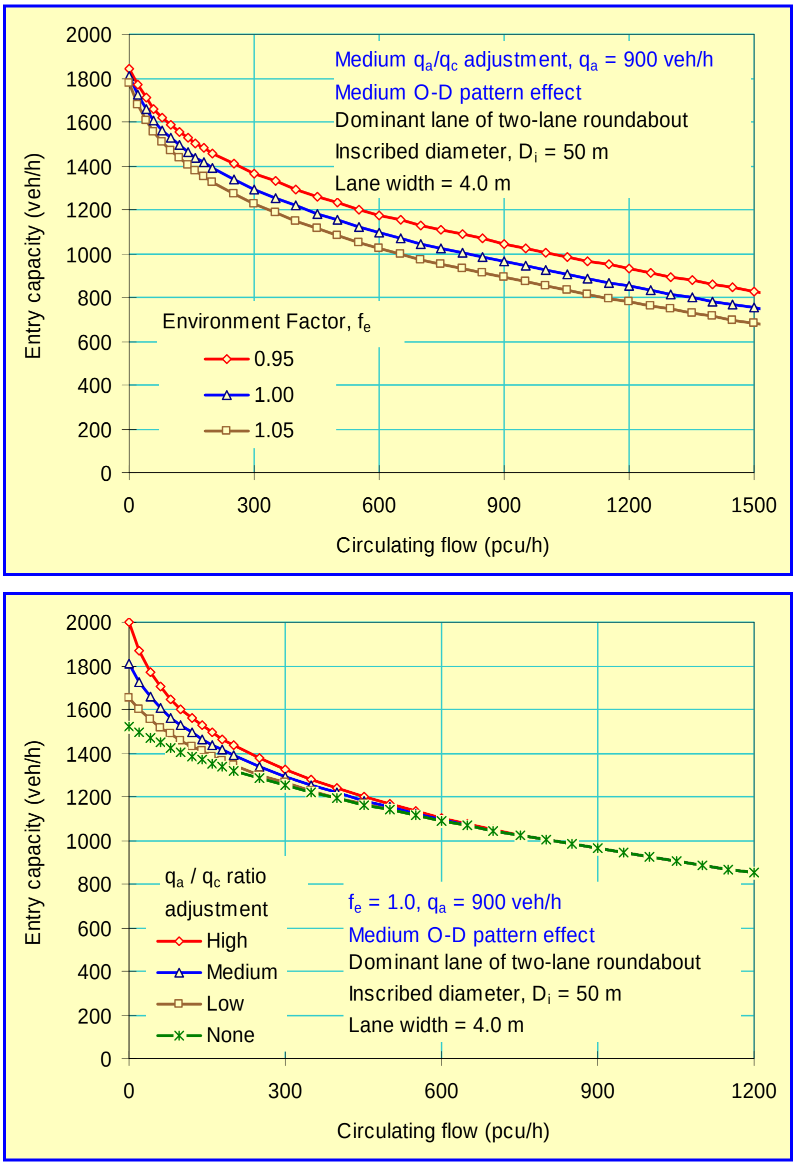

Figure 8.1 - Effect of the Environment Factor and the Adjustment Level for Arrival Flow / Circulation Flow Ratio for the dominant lane of a two-lane roundabout (inscribed diameter = 50 m, average lane width = 4.0 m, Medium O-D pattern effect, entry flow rate = 900 veh/h, no heavy vehicles)

9. CONCLUSION

This paper presented a summary of the differences between the AUSTROADS Roundabout Guide and aaSIDRA methods for roundabout capacity and performance analysis, and discussion of some important aspects of the analysis method where significant differences exist. It is recommended that the enhancements to the roundabout analysis method introduced in aaSIDRA since the publication of the AUSTROADS roundabout guide about ten years ago are taken into account in the revision of the guide.

DISCLAIMER

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