

## REPRINT

# A Roundabout Case Study Comparing Capacity Estimates from Alternative Analytical Models

R. AKÇELIK

### REFERENCE:

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### NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

## ABSTRACT

There has been some controversy about capacity estimates from the gap-acceptance based Australian and Highway Capacity Manual methods and the linear-regression based TRL (UK) (empirical) method. This paper presents a single-lane roundabout case study from the United States to compare capacity estimates from these analytical models. Some contradictory results that can be obtained from these models are highlighted and reasons for differences are discussed. Such systematic differences have important design implications.

The paper discusses the UK roundabout research, and explains why the TRL (UK) Linear Regression model will underestimate capacity for low circulating flows and overestimate capacity for high circulating flows. The TRL (UK) model appears to have been derived with a relatively small number of data points with low circulating flows, and it reflects peculiar effects of the geometric designs of UK roundabouts included in the database used for its development. These highly-flared roundabouts possibly encouraged merging and caused priority reversal at high circulating flows. The aaSIDRA model reflects the more uniform style of modern roundabout designs used in Australia and the USA. Another factor is lack of sensitivity to demand flow patterns in the TRL (UK) Linear Regression and other models. The case study displays an unbalanced flow pattern which contributes to significant differences between the aaSIDRA and other models. Capacity is increased when heavy approach traffic enters against low circulating flow. Dominant circulating flows, originating mostly from a single approach, reduce the entry capacity as evident from the use of metering signals in Australia and the UK to help low-capacity roundabout approaches.

## INTRODUCTION

Methods used for roundabout capacity, performance and level of service analysis are traditionally classified into *gap-acceptance* based methods and *linear-regression* based methods. Examples of the two groups for discussion in this paper are the US Highway Capacity Manual and Australian (aaSIDRA, AUSTRROADS, NAASRA) gap-acceptance based models (1-4), and the TRL (UK) Linear Regression ("empirical") model (5,6). As the use of roundabouts became more common in the USA, differences in results from the analysis software using these methods, namely aaSIDRA representing the Australian and the US HCM gap acceptance methods, and ARCADY and RODEL representing the TRL (UK) Linear Regression Model, became an issue discussed widely among traffic engineering professionals. Fundamental differences between these two approaches to roundabout capacity modeling had already been a subject of debate among researchers and practitioners (7-12).

In a survey of the US practice reported in 1998, Jacquemart (13) found that "the Australian guidelines were followed in two-thirds of cases. For one-third of the cases, the British method was used. However, one-quarter of the respondents checked both the Australian and British methods as sources for design and analysis. ... One respondent mentioned the need to evaluate capacity software programs in use in the United States, indicating contradictory results between SIDRA and RODEL".

Kinzel (14) stated that "the relative merits of these two (Australian and British) methods have been subject to intense debate among roundabout practitioners", and in establishing roundabout guidelines for Missouri DOT, "After much discussion, the committee decided that ... aaSIDRA would be the required software for detailed operational analysis". Many other US authorities have specified aaSIDRA for roundabout capacity analysis (e.g. Caltrans, Florida DOT, Maryland DOT, Oregon DOT, Franklin Regional Council of Governments, Grand Junction and Mesa County Colorado).

Given this background, the purpose of this paper is to highlight the differences between the two groups of models by means of a single-lane roundabout case study and discuss the reasons for the differences in model results. For the practitioner, it is important to understand the reasons behind systematic differences between different models so that judgment can be made about accepting or rejecting results of a particular model in a specific situation.

The case study presented in the paper is a small single-lane roundabout from the United States. This roundabout displays an unbalanced demand flow pattern, which is one of the factors contributing to significant differences between the aaSIDRA and TRL (UK) Linear Regression models. Case studies of multi-lane roundabouts in Australia and UK showing similar model differences can be found in other publications (15-18).

## MODELS CONSIDERED IN THIS PAPER

The results of capacity analyses using the following models are presented in this paper:

1. The *aaSIDRA* gap-acceptance model (2,3,12,15-19) uses gap-acceptance parameters calibrated by field surveys conducted at a large number of modern roundabouts in Australia (3,7,9,20). The follow-up headway and critical gap parameters vary by roundabout geometry and demand flow (both approach and circulating flow) levels as determined using empirical (regression) equations. In addition to the total circulating flow rate, the capacity model is sensitive to variations in approach and circulating lane use, the O-D demand flow pattern, amount of queuing on approach roads before entering the circulating road, and amount of bunching in the circulating stream. It uses a lane-by-lane approach to capacity modeling.
2. The *TRL (UK) Linear Regression* model was developed through surveys conducted at both large conventional design and smaller offside-priority design roundabouts in the UK (5,6,8,1,11,21-24). The intercept and slope of this linear model vary by roundabout geometry. The model uses the total circulating flow rate to determine the total entry capacity per approach. Individual lane details are not accounted for (11,12).
3. The *HCM 2000* model uses fixed gap-acceptance parameters calibrated by limited studies of roundabouts in the USA as well as comparisons with operations in countries with experience in the use of roundabouts (25-27). Follow-up headway and critical gap values of 2.6 s and 4.1 s are used for estimating an *upper limit* of capacity and 3.1 s and 4.6 s are used for estimating a *lower limit* of capacity. These parameters do not vary by roundabout geometry or demand flow levels. The model is limited to single-lane roundabouts with circulating flows up to 1200 pcu/h.
4. The old Australian *NAASRA 1986* model (4) uses fixed gap-acceptance parameters of follow-up headway = 2.0 s and critical gap = 4.0 s. As in the case of the HCM 2000 model, the gap acceptance parameters do not vary by geometry or demand flow levels. This model was based on earlier surveys carried out in Australia.

aaSIDRA version 2.0 is used to obtain capacity estimates for the aaSIDRA gap-acceptance model for the case study reported in this paper. A high level of adjustment for the ratio of entry flow to circulating flow is implemented. This adjustment method is unique to aaSIDRA, and increases the differences between the aaSIDRA and the TRL (UK) Linear Regression and HCM 2000 models for low circulating flow conditions. The capacity estimates for the TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 roundabout models given in this paper are also obtained using the aaSIDRA software which provides results for these models and compares them with the aaSIDRA gap-acceptance model.

Other widely-used roundabout capacity estimation methods using gap acceptance and linear regression models exist in other countries (in particular in Germany, France and Sweden). These are outside the scope of discussion in this paper.

## CASE STUDY - SMALL SINGLE-LANE ROUNDABOUT, USA

A small-size single-lane roundabout from a US city is analyzed (see *Figure 1*). The exact location of this roundabout is not disclosed, and the road names are modified due to confidentiality reasons. While the demand flow pattern has been kept similar, traffic volumes have been modified to some extent for better demonstration of model differences (see *Figure 2*).

### Data for the Case Study

This roundabout presents an interesting case of unbalanced flows with heavy North - South through movement volumes on Lessur Ave, and low volumes on East and West approaches (Selwon St) as seen in *Figure 2*. This situation may arise when a roundabout is considered as an alternative treatment to replace two-way stop control at a major road intersection where low minor road volumes result from stop control under high major road volumes. Thus, this case presents a combined case of (i) *high entry flow - low circulating flow* and (ii) *highly directional (unbalanced) flows*. These factors contribute to significant differences in estimates from the aaSIDRA and other capacity models.

Parameters describing the roundabout geometry are summarized in *Table 1*. Entry radius values were specified as right-turn negotiation radius values. aaSIDRA determined the negotiation radius values for through and left-turn movements, and calculated the corresponding negotiation speed and distance values for all movements. All approach and downstream distances were specified as 1500 ft, and all approach and exit cruise speeds were specified as 30 mph.

The analysis was carried out for peak 15-min flow conditions which were specified as input (*Figure 2*). For the aaSIDRA model, minimum capacity under very heavy demand flow conditions was specified as 2.5 veh/min (150 veh/h) per lane.

### Capacity Estimates for the Case Study

Estimates of capacity, degree of saturation ( $v/c$  ratio) and practical spare capacity for the aaSIDRA, TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models are given in *Table 2*. The *HCM 2000 Average* results given in *Table 2* are based on capacities calculated as the average of *Upper* and *Lower* capacity values. The capacity values given in *Table 2* are affected by capacity constraint due to

$v/c > 1$  (oversaturated approach) cases. Practical spare capacities are based on a practical (target)  $v/c$  ratio of 0.85 (negative when this target is exceeded).

*Figure 3* shows the comparison of aaSIDRA and TRL (UK) model capacity results. Differences in circulating flows are due to different capacity constraint effects. It is seen in *Table 2* and *Figure 3* that, while the results for Northbound and Westbound approaches are close for all models, there are significant differences in results for Southbound and Eastbound approaches:

1. The Southbound approach is oversaturated according to the TRL (UK) Linear Regression and HCM 2000 models whereas the aaSIDRA and NAASRA 1986 models estimate sufficient capacity to handle the high flow rate on this approach (e.g. TRL (UK) Linear Regression model: 1225 veh/h,  $v/c = 1.10$  vs aaSIDRA: 1708 veh/h,  $v/c = 0.79$ ).
2. The aaSIDRA model indicates oversaturated conditions for the Eastbound approach whereas the TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models estimate sufficient capacity for this approach (e.g. TRL (UK) Linear Regression model: 533 veh/h,  $v/c = 0.67$  vs aaSIDRA: 328 veh/h,  $v/c = 1.09$ ).

These differences are explained below.

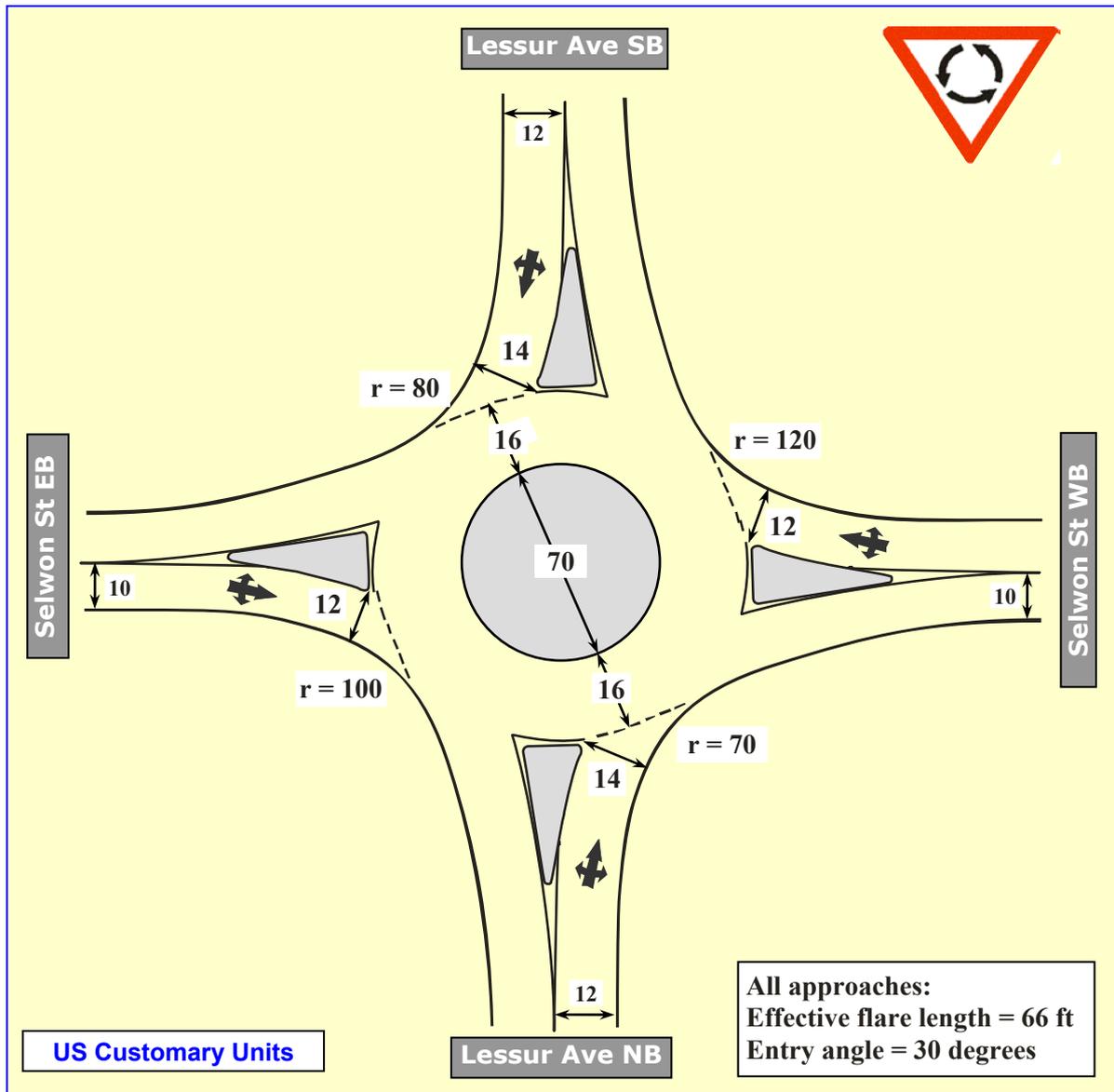


Figure 1 - Case Study - Single-Lane Roundabout, USA:  
Roundabout geometry

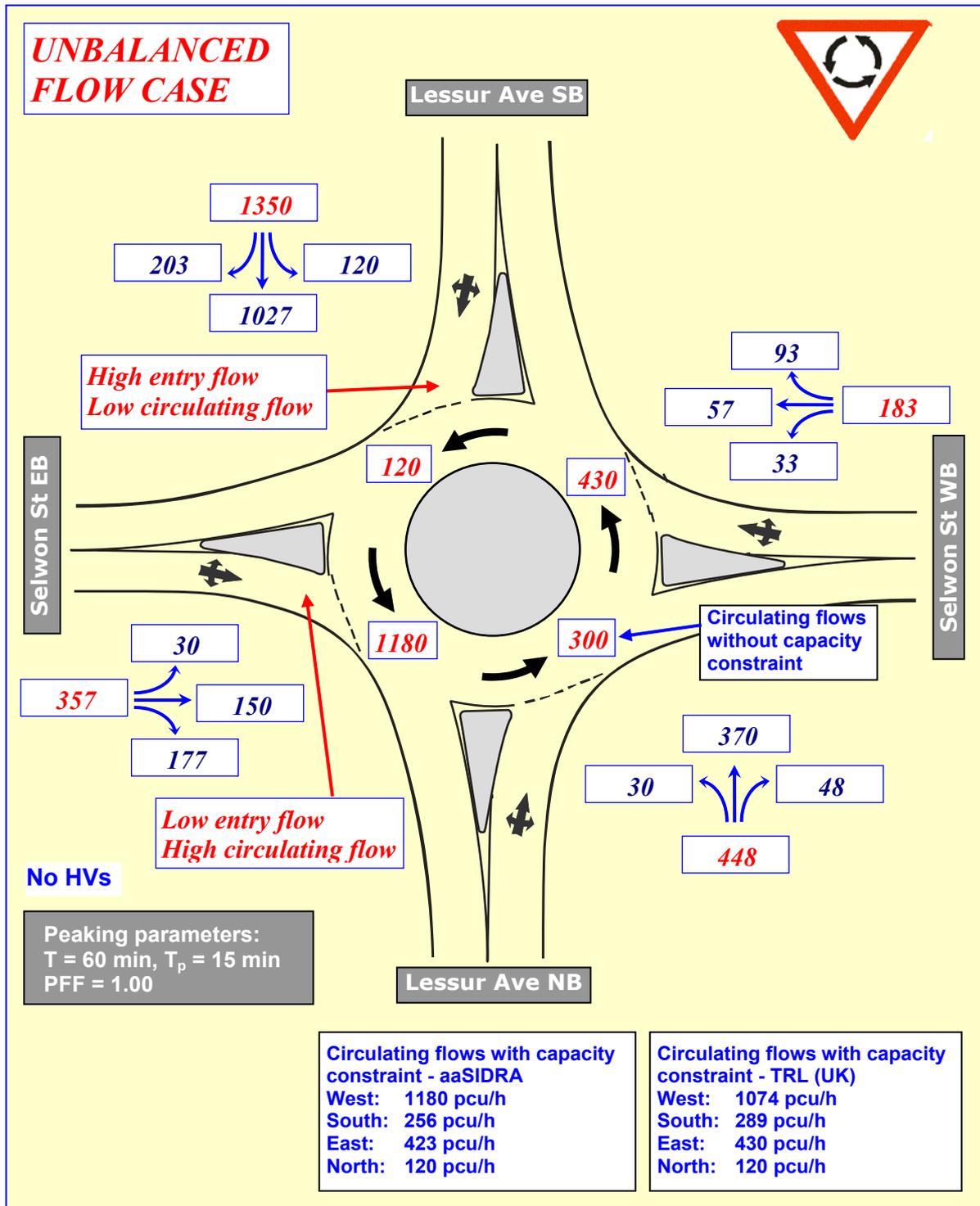


Figure 2 - Traffic volumes (peak 15-minute flow rates in veh/h) for the Case Study (Single-Lane Roundabout, USA)

**Table 1 - Roundabout geometry data for the Case Study (Single-lane roundabout, USA)**

Approach ID	Approach Name	Average entry lane width	Total entry width	App. half width	Flare length (effective)	Entry radius	Entry angle
		w <sub>L</sub> (ft)	w <sub>e</sub> (ft)	w <sub>a</sub> (ft)	L <sub>f</sub> (ft)	r <sub>e</sub> (ft)	Φ <sub>e</sub> (deg)
W	Selwon St EB	12 (3.66 m)	12 (3.66 m)	10 (3.16 m)	66 (20 m)	100 (30.5 m)	30
S	Lessur Ave NB	14 (4.27 m)	14 (4.27 m)	12 (3.77 m)	66 (20 m)	70 (21.3 m)	30
E	Selwon St WB	12 (3.66 m)	12 (3.66 m)	10 (3.16 m)	66 (20 m)	120 (36.6 m)	30
N	Lessur Ave SB	14 (4.27 m)	14 (4.27 m)	10 (3.77 m)	66 (20 m)	80 (24.4 m)	30
		Inscribed diameter	Central island diameter	Circulating road width	No of entry lanes	No of circulating lanes	
		D <sub>i</sub> (ft)	D <sub>c</sub> (ft)	w <sub>c</sub> (ft)	n <sub>e</sub>	n <sub>c</sub>	
W	Selwon St EB	102 (31.1 m)	70 (21.3 m)	16.0 (4.9 m)	1	1	
S	Lessur Ave NB	102 (31.1 m)	70 (21.3 m)	16.0 (4.9 m)	1	1	
E	Selwon St WB	102 (31.1 m)	70 (21.3 m)	16.0 (4.9 m)	1	1	
N	Lessur Ave SB	102 (31.1 m)	70 (21.3 m)	16.0 (4.9 m)	1	1	

Data in metric units are shown in brackets.

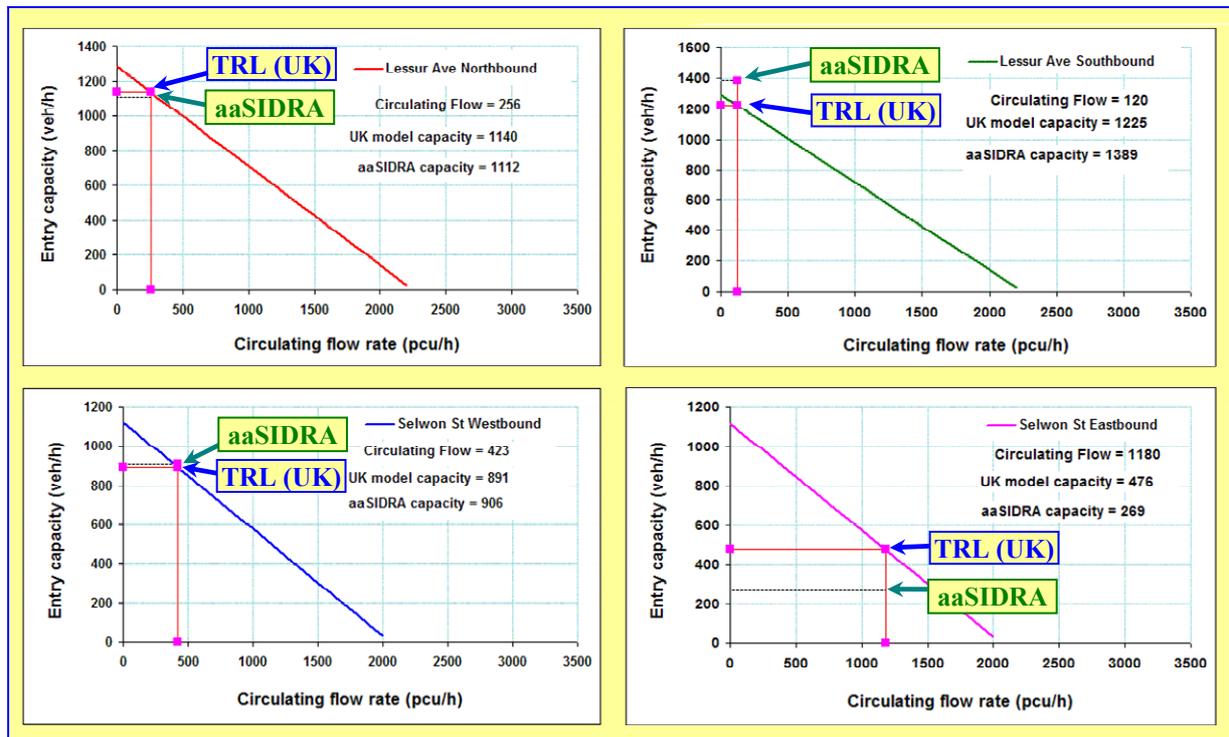
**Table 2 - Capacity estimates from various models for the Case Study (Single-lane roundabout, USA)**

App. ID	Approach Name	Approach flow rate (veh/h)	aaSIDRA			TRL (UK) Linear Regression		
			Capacity (veh/h)	Degree of saturation (v/c ratio)	Practical Spare Capacity ( $x_p = 0.85$ )	Capacity (veh/h)	Degree of saturation (v/c ratio)	Practical Spare Capacity ( $x_p = 0.85$ )
<b>W</b>	<b>Selwon St EB</b>	<b>357</b>	<b>269</b>	<b>1.325</b>	<b>-36%</b>	<b>533</b>	<b>0.669</b>	<b>27%</b>
S	Lessur Ave NB	448	1112	0.403	111%	1121	0.400	113%
E	Selwon St WB	183	906	0.202	321%	888	0.206	313%
<b>N</b>	<b>Lessur Ave SB</b>	<b>1350</b>	<b>1389</b>	<b>0.972</b>	<b>-13%</b>	<b>1225</b>	<b>1.102</b>	<b>-23%</b>

App. ID	Approach Name	Approach flow rate (veh/h)	NAASRA 1986			HCM 2000 Average		
			Capacity (veh/h)	Degree of saturation (v/c ratio)	Practical Spare Capacity ( $x_p = 0.85$ )	Capacity (veh/h)	Degree of saturation (v/c ratio)	Practical Spare Capacity ( $x_p = 0.85$ )
<b>W</b>	<b>Selwon St EB</b>	<b>357</b>	<b>439</b>	<b>0.813</b>	<b>5%</b>	<b>544</b>	<b>0.656</b>	<b>30%</b>
S	Lessur Ave NB	448	1378	0.325	161%	1010	0.444	92%
E	Selwon St WB	183	1213	0.151	463%	895	0.205	315%
<b>N</b>	<b>Lessur Ave SB</b>	<b>1350</b>	<b>1625</b>	<b>0.831</b>	<b>2%</b>	<b>1155</b>	<b>1.169</b>	<b>-27%</b>

Capacity constraint applies to all models (different circulating flows used as a result)



**Figure 3 - Comparison of capacity estimates from the aaSIDRA and TRL (UK) Linear Regression Models for the Case Study (Single-Lane Roundabout, USA): TRL (UK) capacities in this figure differ from those in Table 2 slightly since they are based on aaSIDRA circulating flows with capacity constraint (see Figure 2)**

### **Southbound Approach**

For the Southbound approach, aaSIDRA estimates a relatively high capacity value because:

- (i) the circulating flow rate in front of this approach is very low (120 pcu/h, corresponding to a large average headway of 30 s), and
- (ii) the ratio of entry lane flow rate to circulating flow rate is very high (1350 / 120).

When the circulating flow rate is very low and the entry lane flow rate is very high, the aaSIDRA model decreases the follow-up headway as a function of the ratio of entry flow rate to circulating flow rate, effectively increasing the entry capacity. Heavy entry flow rate (1350 veh/h) means that these vehicles will queue (slow down) before entering the roundabout when interrupted by circulating stream vehicles but they will be discharged from the queue into very long gaps available in the circulating flow at a high *saturation flow rate*. In terms of gap-acceptance process, the results can be explained with a saturation flow rate of  $s = 3600 / \beta = 1560 \text{ veh/h}$ , where  $\beta = 2.31 \text{ s}$  is the follow-up (or *saturation*) headway. This saturation flow rate obtained with a medium level of adjustment for the ratio of entry lane flow rate to circulating flow rate is reasonable. The corresponding follow-up headway is much larger than those observed under the pressure of high circulating flow conditions (follow-up headways around 1.0 s were observed in surveys). In the aaSIDRA model for the Southbound approach, the *effective unblock ratio* (based on average time when acceptable gaps are available) is  $u = 89.0$  per cent, and the entry capacity is  $Q_e = u s = 0.890 \times 1560.3 = 1389 \text{ veh/h}$ . Applying the same effective unblock ratio to the capacity estimated by the TRL (UK) Linear Regression model, a saturation flow rate of  $s = Q_e / u = 1225 / 0.890 = 1376 \text{ veh/h}$  or a follow-up headway of  $\beta = 3600 / 1363 = 2.62 \text{ s}$  can be calculated. Note that these are *implied* parameters only since the TRL (UK) Linear Regression model does not use gap-acceptance parameters.

It can be shown that the estimated or implied follow-up headways correspond to *driver queue response (reaction) times* of **1.5 s** for aaSIDRA model, **1.2 s** for the NAASRA 1986 model, **1.8 s** for the TRL (UK) Linear Regression model, and **2.1 s** for the HCM 2000 Average model. The response time parameter explains why high capacity values can be achieved under the conditions of heavy entry flow against low circulating flow by the aaSIDRA and NAASRA 1986 models ([more alert drivers with smaller reaction times](#)) and low capacity values are estimated by the TRL (UK) Linear Regression and HCM 2000 models ([more relaxed drivers with larger reaction times, accepting to wait in a long queue resulting from oversaturated conditions in spite of very large gaps available in the circulating stream](#)).

The analytical method used to estimate the driver reaction time from follow-up headway will be explained in a separate publication. A jam spacing of 23 ft (7.0 m) per vehicle in the approach queue and a queue discharge (saturation) speed of 20.2 mph (32.5 km/h) were assumed to derive the values quoted above. Driver queue response (reaction) times in the range 0.8 to 1.4 s have been observed at signalized intersections in Australia, USA and Finland. Future research at roundabouts could investigate this parameter through field studies at roundabouts.

### **Eastbound Approach**

For the Eastbound approach, aaSIDRA estimates oversaturated conditions ( $v/c > 1$ ) due to heavy circulating flow (1180 pcu/h) with almost all vehicles (97 per cent) coming from the Southbound (dominant) approach. For such unbalanced conditions, aaSIDRA applies an Origin-Destination (O-D) factor, reducing the gap-acceptance capacity significantly. In the case of the Eastbound approach, a significant O-D factor (0.562) applies reducing the gap-acceptance capacity of 480 veh/h (determined assuming no unbalanced flow effects) down to 269 veh/h.

Generally, the aaSIDRA model estimates lower capacities for approaches with circulating flows that consist of vehicles coming mostly from the same approach, whereas other models considered in this paper are not sensitive to the origin-destination pattern of the streams contributing to a circulating flow. Thus, in the TRL (UK) Linear Regression and the HCM 2000 and NASRA 1986 gap-

acceptance models, there is no distinction for unbalanced or balanced flows, and they suggest that there is sufficient capacity for the Eastbound approach in this particular case.

There are many examples of roundabouts with unbalanced flow patterns in Australia, where part-time roundabout metering signals are used to create gaps in the circulating stream in order to solve the problem of excessive queuing and delays at approaches affected by highly directional flows. See the Australian and UK case studies given in other publications presenting cases of roundabouts with unbalanced flow patterns where the TRL (UK) Linear Regression model failed to estimate severe congestion problems (15-18). A recent study of a roundabout in Denmark (28) concluded that "the lane allocation of circulating flow did have a significant impact on capacity, particularly at large circulating flow rates. This implies that the origin and destination of the flow constituting the circulating traffic must be accounted for in estimating capacity."

It appears that the problem of unbalanced flows is quite common and the signalised roundabout solution has been used extensively in the UK as well (29-34). Huddart's (29) comments published as early as 1983 are well in line with the aaSIDRA model: "...the proper operation of a roundabout depends on there being a reasonable balance between the entry flows. ... an uninterrupted but not very intense stream of circulating traffic can effectively prevent much traffic from entering at a particular approach." and "The capacity of roundabouts is particularly limited if traffic flows are unbalanced. This is particularly the case if one entry has very heavy flow and the entry immediately before it on the roundabout has light flow so that the heavy flow proceeds virtually uninterrupted. This produces continuous circulating traffic which therefore prevents traffic from entering on subsequent approaches."

Generally, the extent of the unbalanced flow problem is likely to be underestimated by the TRL (UK) Linear Regression, HCM 2000 and similar models that (i) estimate low capacity for approaches with high entry flows against low circulating flows, and (ii) do not have sensitivity to the origin-destination pattern. The level of capacity overestimation at the downstream approach will increase when the upstream approach is estimated to be oversaturated, in which case, *capacity constraint* would be applied to the upstream approach. Capacity constraint means that if the arrival (demand) flow on an approach exceeds capacity, only the capacity flow rate is allowed to enter the roundabout circulating road. This would lead to an unrealistically low circulating flow in front of the downstream approach, and therefore to an increased capacity estimate for the downstream approach.

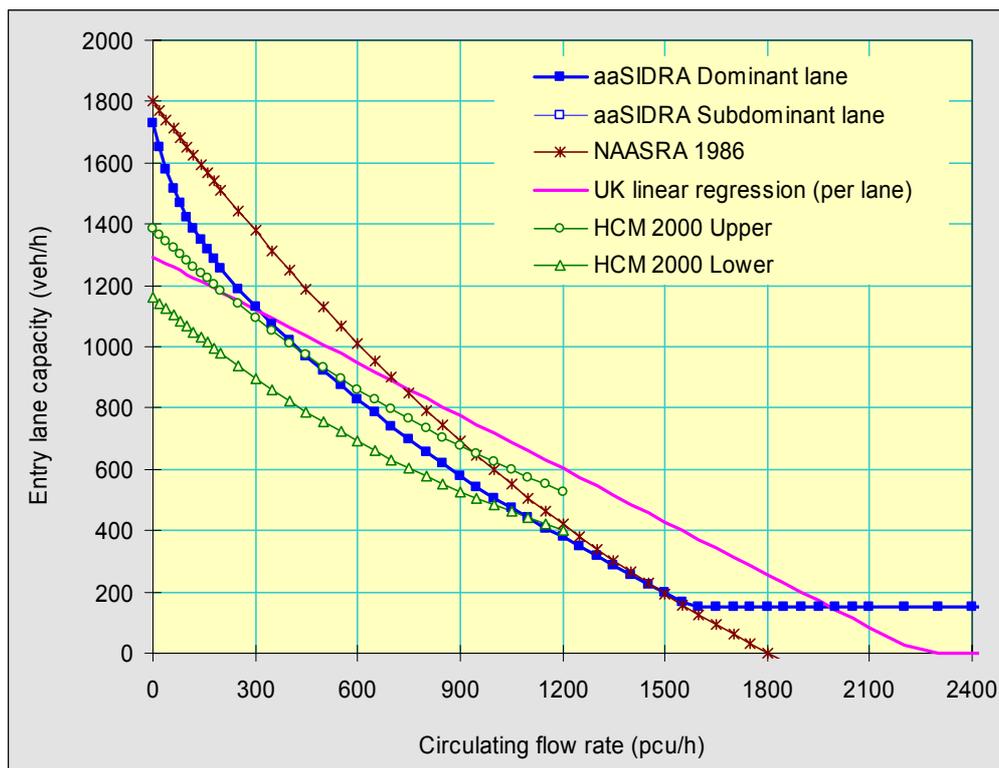
The case study given in this paper presents an example of this. The TRL (UK) Linear Regression model estimates oversaturated conditions for the Southbound approach (capacity = 1225 veh/h > arrival flow = 1350 veh/h), and therefore, the flow rate entering the roundabout is limited to 1225 veh/h. The contribution of this approach flow to the circulating flow in front of the Eastbound approach is reduced from 1147 to 1041 pcu/h, and the total circulating flow rate for this approach is reduced from 1180 pcu/h to 1074 pcu/h. As a result, the capacity of the Eastbound approach is increased from 476 veh/h (with a circulating flow rate of 1180 veh/h) to 533 veh/h (with a reduced circulating flow rate of 1074 veh/h).

Combination of the above factors is seen to give contradictory results from the aaSIDRA and TRL (UK) Linear Regression (also the HCM 2000) capacity models in this case study. Although the volumes for this case were chosen to exaggerate the model differences for the purpose of clearer explanation of the reasons behind the differences, such model differences are quite common in many real-life cases. In fact, model enhancements to allow for unbalanced flow effects were introduced after research was conducted (15,16,35-37) following reports received from many practitioners that overoptimistic results were obtained from the Australian method (3) which did not allow for unbalanced flow effects.

## COMMENTS ON MODEL DIFFERENCES

Comparison of entry capacities estimated by the aaSIDRA, TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models for a single-lane roundabout case is shown in *Figure 4*. This is for the Southbound approach of the case study roundabout given in this paper. The aaSIDRA capacity curve in *Figure 4* assumes medium O-D flow pattern effect and a moderate level of adjustment for the ratio of entry lane flow rate to circulating flow rate (changes in these factors change the capacity curve). *Figure 4* is quite typical for a single-lane roundabout, and shows that:

- (i) the NAASRA 1986 model appears to provide high capacity estimates for low to medium conditions;
- (ii) the aaSIDRA capacity estimates are between the HCM 2000 Upper and Lower capacity estimates except for very low circulating flows;
- (iii) the aaSIDRA model estimates approach the NAASRA 1986 model values for very low circulating flow rates, move from the HCM 2000 Upper capacity values towards the HCM Lower capacity values as the circulating flow increases, and are close to the NAASRA 1986 values for high circulating flow values;
- (iv) the TRL (UK) Linear Regression model estimates are higher than the aaSIDRA and HCM 2000 model values except for very low circulating flow, and its capacity estimates are higher than estimates from all other models for high circulating flows.



**Figure 4 - Comparison of entry capacities estimated by the aaSIDRA, TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models for a typical single-lane roundabout case (aaSIDRA subdominant lane not applicable for single lane approach)**

Possible reasons for the TRL (UK) Linear Regression model to give lower capacities at low circulating flows and higher capacities at high circulating flows as seen in *Figure 4* include the following:

- (i) reliance on a purely *statistical (regression) approach* in its development rather than an analytical approach supported by a statistical approach,
- (ii) the *peculiarities of the geometric features* of the roundabouts included in the database used for capacity model derivation, and
- (iii) the use of a *linear regression* model that is inevitably biased when trying to describe a relationship which is likely to be of an exponential nature when very low and high circulating flow conditions are accounted for appropriately.

These are discussed considering low and high circulating flow regions.

### **TRL (UK) Linear Regression Model Capacity Estimates: Low Circulating Flow Rates**

With the TRL (UK) Linear Regression model, it is difficult to avoid underestimation of capacity (overestimation of driver response times) at very low circulating flow conditions due to its linearity combined with the "best fit" nature of the regression method. The nature of this regression relationship is possibly biased since it is likely that the database it is derived from includes a relatively small number of data points with low circulating flow rates (and probably very few data points with high arrival flow rate against low circulating flow rate). This is because capacity observations for the TRL (UK) Linear Regression model relied on using data from saturated approaches which are difficult to find under low circulating flow conditions.

Examples from two UK roundabout research reports shown in *Figure 5* indicate that relative frequencies of data at circulating flows below 600 pcu/h were very small (23,38). This is likely to be similar for the database used in deriving the TRL (UK) Linear Regression model for at-grade roundabouts (5). These examples also show how the "observed regression line" can underestimate capacity at low circulating flows. In *Figure 5(b)*, the broken line representing the TRL (UK) Linear Regression model for at-grade roundabouts displays substantial underestimation of capacity at low circulating flows and overestimation of capacity at high circulating flows for a different type of roundabout design. This is discussed further below.

### **TRL (UK) Linear Regression Model Capacity Estimates: High Circulating Flow Rates**

Contrary to the low circulating flow region, the TRL (UK) Linear Regression model estimates higher capacity than other models in the high circulating flow region. The reasons are different from those for low circulating flows.

The TRL (UK) research leading to the linear regression model was preoccupied with the effect of roundabout geometry:

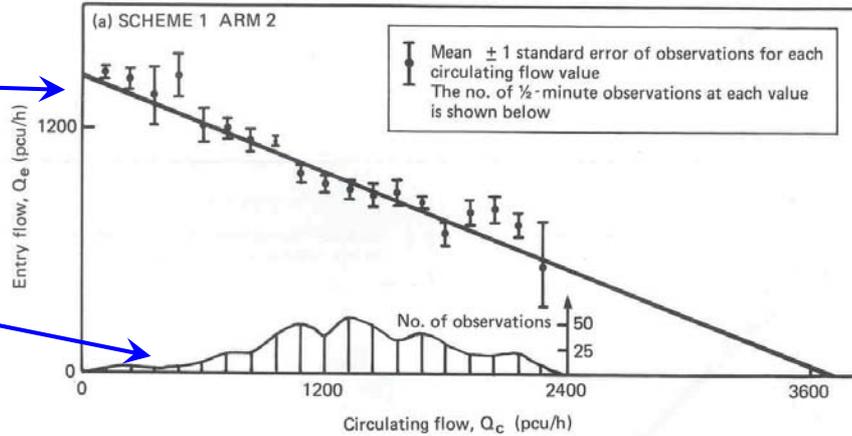
*"The intention was to provide a single method for estimating the capacity of entries to all at-grade roundabouts. The unified formula was developed using observations made on the TRRL Test Track and at a large number of public road sites; these observations covered a wide range of values of those geometric parameters which were found to affect the entry capacity." (23 p.1).*

*"... capacity prediction for both 'conventional' and 'offside-priority' roundabouts has thus been brought together into a common framework in which capacity is predicted entry by entry. However, the two types are designed according to geometric principles evolved as a result of differently perceived mechanisms - weaving for conventional designs and gap-acceptance for offside priority designs. Consequently their characteristic geometric features and sizes are different: conventional roundabouts have large and often irregularly shaped central islands, parallel sided weaving sections and unflared entries (usually two-lane), whereas offside priority designs have smaller, usually circular, central islands and flared approaches." (5 p.3).*

**(a) At-grade roundabout in Wincheap, Canterbury, UK (38)**

*Regression line underestimates capacity at low circulating flows*

*Small number of data points at low circulating flows*

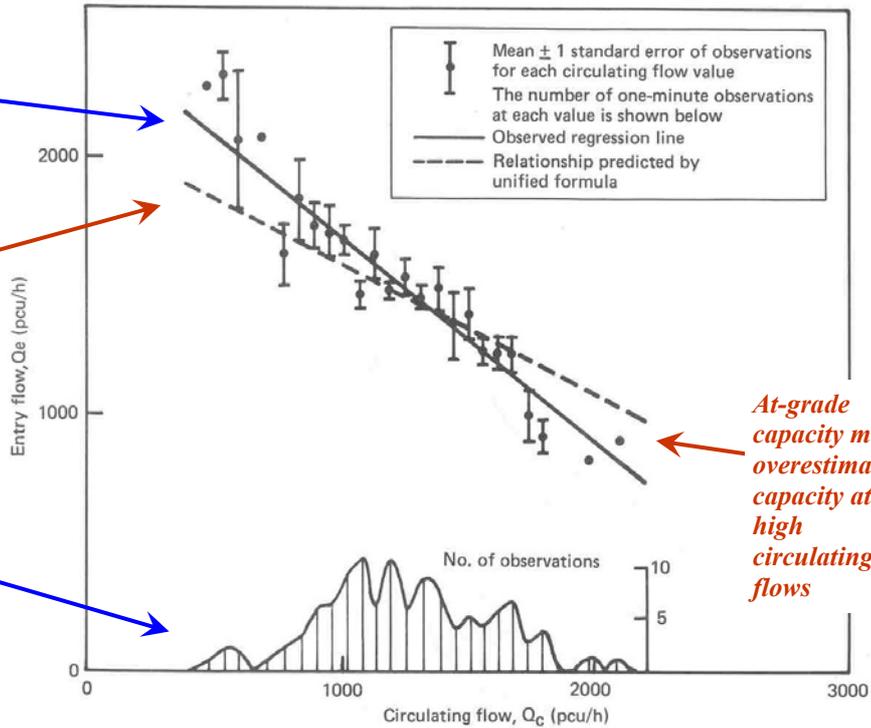


**(b) Grade-separated roundabout in Bradford, UK (23)**

*Regression line underestimates capacity at low circulating flows*

*At-grade capacity model further underestimates capacity at low circulating flows*

*Small number of data points at low circulating flows*



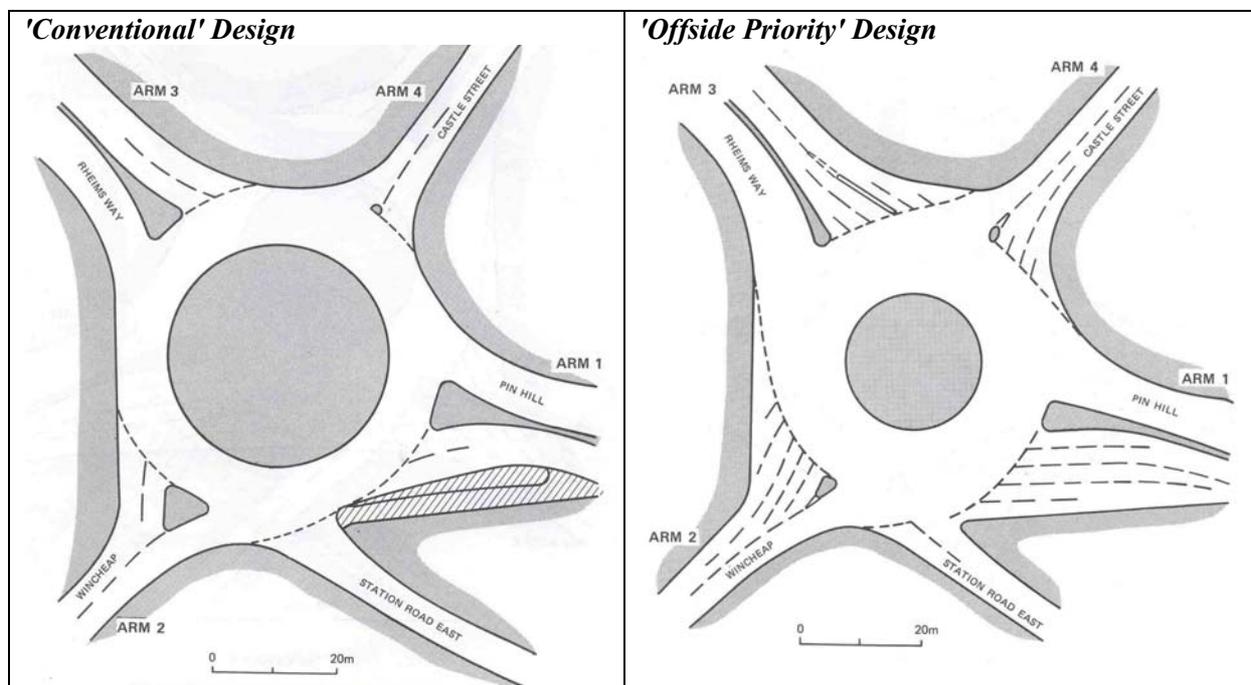
*At-grade capacity model overestimates capacity at high circulating flows*

**Figure 5 - Data from roundabout capacity surveys at UK roundabouts**

Examples of the two design types used in capacity measurements for the TRL (UK) Linear Regression model discussed in the above quote are shown in *Figure 6 (38)*. Large numbers of both types of roundabouts were included, and *represented equally*, in the TRL capacity database. This diversity of roundabout designs with a very wide range of geometric parameters may have contributed to the linearity of the TRL (UK) capacity model due to the regression (best fit) approach used. Other reasons for the linearity would be the lack of data at low circulating flow range (discussed above) and aggregation of data for all lanes of multi-lane approaches as well as flared single lane approaches (*16 Section 7.4.2*).

The approach-based method adopted for the TRL (UK) Linear Regression model was an improvement over the method that existed then, which estimated capacity of the roundabout as a whole (*16 p.2*). However, lack of sensitivity to variations in lane arrangements (e.g. difference between exclusive and shared lanes) and to possible lane underutilisation effects cause serious capacity estimation problems with the TRL (UK) Linear Regression model (*11,12*).

As seen in *Figure 6*, a highly flared offside priority design means a significantly increased number of entry lanes (this would be modeled as short lanes in aaSIDRA). This arrangement can increase the entry capacity substantially. Flared offside priority designs with very low entry angles (range 0 to 77 degrees) and large entry radius values (range 3.4 m, or 11 ft to  $\infty$ ) would encourage merging behavior and possibly induce priority reversal at high circulating flow rates. Similarly, conventional designs encouraged merging behavior according to the TRL research reports. It appears that capacity of some continuous entry lanes, expected to contribute to high capacities observed at large circulating flows, were also included in the TRL database. It also seems that various experimental designs used by TRL encouraged merging and this was observed at high circulating flows (*5 p.4 and 22 p.4*). All these factors must have contributed to high capacity values observed at high circulating flow rates. Increased capacities at high circulating flows combined with the lack of data at low circulating flows would have contributed to the linearity of the TRL (UK) regression model.



**Figure 6 - Examples of 'Conventional' and 'Offside Priority' roundabout designs used in capacity measurements for TRL (UK) linear regression model (38)**

Merging and priority reversal observed at the UK roundabouts were stated among the reasons for not using the gap-acceptance methodology, in addition to the gap-acceptance parameters not being sensitive to roundabout geometry and circulating flow level in the gap-acceptance models that existed at the time (5,8,10). These concerns appear to have resulted from the geometric design features adopted at roundabouts included in the UK roundabout capacity surveys.

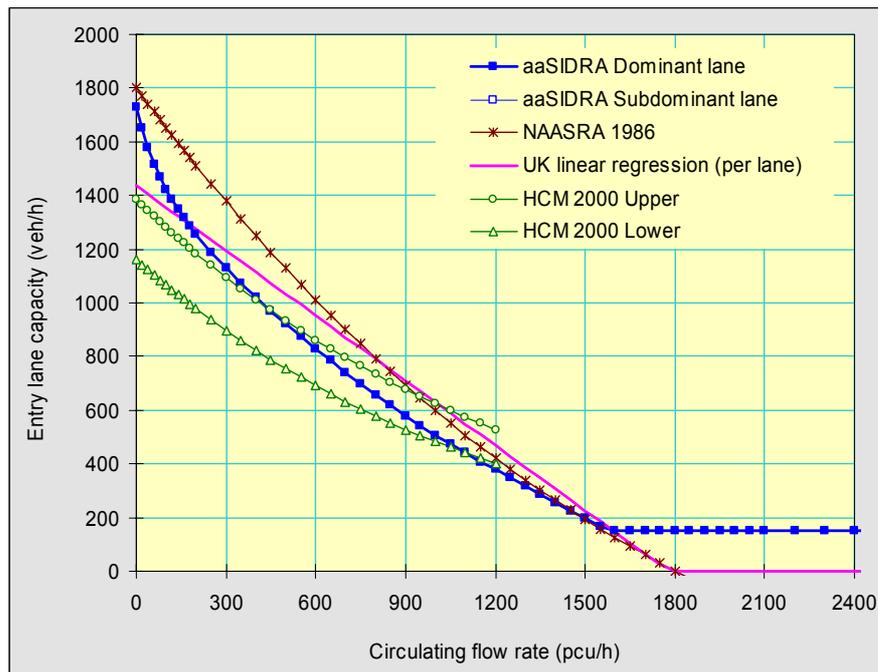
It is interesting to note that UK research on grade-separated roundabouts led to a modified capacity formula that estimates lower capacity at high circulating flow rates (requiring a much higher slope of the regression line as seen in Figure 5(b)). Semmens (23 p.3) suggested that "This result is consistent with the behavioral mechanism that drivers at grade-separated roundabout entries appear to conform more to strict 'give-way' behavior, which leads to steeper entry-circulating flow relationship, than to more usual mixture of 'give-way' and 'merging' at the larger (conventional) at-grade roundabouts." and explained this with poorer sight distances associated with extra barriers and supports at these roundabouts. Data given by Semmens (23 p.10) indicates that these roundabouts had negligible or no flaring (23 p.10), and this is probably the reason for more strict give-way (yield) behavior and lack of merging that explains lower capacities observed at high circulating flows.

Semmens (23 p.6) investigated the effect of changes to approach geometry at two grade-separated roundabouts. These changes "caused substantial changes in give-way behavior, with a marked swing towards merging movements.", and resulted in increased capacity at high circulating flow rates (slope of the regression line was reduced).

Thus, the type of roundabout design clearly affects the driver behavior and the resulting capacity relationship. The TRL (UK) Linear Regression model reflects the conventional and offside-priority designs used in that country at the time, which seem to have encouraged merging behavior as discussed above. It is believed that these roundabout designs are not representative of modern roundabout designs adopted in Australia (3,39,40) and the USA (13,41-43), whose approaches are more like the unflared entries at *grade-separated* roundabouts discussed by Semmens (21).

Semmens (23) suggested a modified capacity formula for *grade-separated* roundabouts where the capacity at zero circulating flow is increased by a factor 1.11, and the slope of the regression line as predicted by the TRL (UK) Linear Regression model for *at-grade* roundabouts is increased by a factor of 1.40. The effect of this change can be seen in Figure 5(b).

Figure 7 shows that the TRL (UK) Linear Regression model with these changes gives closer results to other models, especially for high circulating flows (for the Southbound approach in the case study as for Figure 4). Using the "grade-separated" roundabout model option, the TRL (UK) Linear Regression model was able to estimate oversaturated conditions for the Eastbound approach in the case study described in this paper agreeing with the aaSIDRA model.



**Figure 7 - Comparison of entry capacities estimated by the TRL (UK) Linear Regression model for "grade-separated" roundabouts with the aaSIDRA, HCM 2000 and NAASRA 1986 model estimates for a typical single-lane roundabout case : this figure displays closer results between the TRL (UK) Linear Regression and other models (compare with Figure 4)**

## CONCLUDING REMARKS

The differences between the aaSIDRA, TRL (UK) Linear Regression, HCM 2000 and old Australian NAASRA 1986 capacity models have been highlighted and possible reasons for the differences in model results have been discussed by means of a single-lane roundabout case study from the United States. This roundabout displays an unbalanced demand flow pattern with heavy North - South through movement volumes and low volumes on East and West approaches. This is one of the factors contributing to significant differences between the aaSIDRA and other models.

For this roundabout, the Southbound approach is oversaturated according to the TRL (UK) Linear Regression and HCM 2000 models whereas the aaSIDRA and NAASRA 1986 models estimate sufficient capacity to handle the high demand flow rate on this approach. On the other hand, the aaSIDRA model indicates oversaturated conditions for the Eastbound approach whereas the TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models estimate sufficient capacity for this approach.

These differences are explained with lack of sensitivity to demand flow patterns in the TRL (UK) Linear Regression, HCM 2000 and NAASRA 1986 models which determine capacity as a function of the total circulating flow irrespective of the entry demand flow rate level or the origin-destination and queuing levels of the streams contributing to the circulating flow.

It is suggested that, for the combined "high entry lane flow and low circulating flow" conditions, the aaSIDRA model implies alert drivers with smaller reaction times (**1.5 second**) whereas the TRL (UK) Linear Regression and HCM 2000 models imply relaxed drivers with larger reaction times (**1.8 seconds**), accepting to wait in a long queue in congested conditions in spite of very large gaps available in the circulating stream.

The TRL (UK) Linear Regression model underestimates capacity for low circulating flow rates and overestimates capacity for high circulating flow rates by its nature, i.e. being a linear regression model, especially as it appears to have been derived with a relatively small number of data points with low circulating flow rates and as it reflects the *peculiar geometric designs* of UK roundabouts included in the capacity database. These highly flared roundabouts with low conflict angles possibly encouraged merging behavior and caused *priority reversal* at high circulating flows. As a result, the TRL (UK) Linear Regression model overestimates capacity at high circulating flow rates compared with the aaSIDRA model that reflects the more uniform style of modern roundabout designs used in Australia and the USA. **In fact, aaSIDRA applies priority emphasis due to unbalanced demand flow pattern in the case of Southbound and Eastbound approaches.** These factors contribute to the inevitability of bias in a *linear regression* model (**which represents average conditions**) when trying to describe a relationship which is likely to be exponential when very low and high circulating flow rates as well as unbalanced flow conditions are accounted for appropriately.

These fundamental differences between the aaSIDRA and TRL (UK) Linear Regression Models explain the contradictory results that may be obtained from these models. Such systematic model differences have important practical design implications.

The aaSIDRA model estimates capacity according to the give-way (yield) behavior, and allows for the effect of highly directional circulating flows originating mostly from a single approach, thus reducing the entry capacity for such unbalanced flow conditions. The TRL (UK) Linear Regression model has been found to be too optimistic and has failed to predict congested conditions observed at many roundabouts in Australia and the UK (*15-17*). Dominant circulating flows reduce the entry capacity as evident from the use of metering signals in Australia and the UK to help low-capacity roundabout approaches (*17,18, 29-34*).

This paper focused on comparison of analytical models. Microsimulation models offer a great potential for modeling complex gap-acceptance situations experienced in many situations in urban traffic. Modeling issues discussed in this paper are also applicable to microsimulation models since driver behavior rules and gap-acceptance parameter values used in microsimulation will affect the resulting capacity and performance estimates (*44*). Comparisons of capacity and performance estimates from different microsimulation models and between microsimulation and analytical models are also recommended.

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