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ROUNDABOUTS - Comments on the SIDRA INTERSECTION Model and the UK TRL Linear Regression Model

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It is not who is right, but what is right, that is important.
Thomas Huxley

INTRODUCTION

In the USA where roundabouts are relatively new, there has been some controversy regarding the SIDRA INTERSECTION roundabout model and the UK TRL regression model (the basis of the roundabout model used in the RODEL and ARCADY software packages) for estimating the capacity of roundabouts.. This note presents Dr Akçelik's views on the subject.

This document includes discussions on related issues of priority sharing and priority emphasis, model calibration in SIDRA INTERSECTION, and reasons for shortcomings of the UK TRL regression model.

Also see the following short document for a table comparing main features of three roundabout models, namely the Australian model as implemented in the SIDRA INTERSECTION software, the HCM 2010 model described in the 2010 Highway Capacity Manual and the UK TRL model implemented in the RODEL and ARCADY software packages:

AKÇELIK, R. (2011). **Roundabout Model Comparison Table**. Akcelik and Associates Pty Ltd, Melbourne, Australia.

In relation to this discussion, various websites promoting the RODEL software package in the USA include misleading statements about the SIDRA INTERSECTION method for roundabout capacity analysis. Such statements present SIDRA INTERSECTION as "simple theoretical gap-acceptance model" using arguments based on very old articles, which are not relevant to SIDRA INTERSECTION. In addition to the discussion in this document, refer to the publications by the author listed in the REFERENCES section. In particular, refer to:

AKÇELIK, R. (1997). **Lane-by-lane modelling of unequal lane use and flares at roundabouts and signalised intersections: the SIDRA solution**. *Traffic Engineering and Control*, 38 (7/8), pp 388-399.

AKÇELIK, R. (2003). **A Roundabout Case Study Comparing Capacity Estimates from Alternative Analytical Models**. Paper presented at the *2nd Urban Street Symposium*, Anaheim, California, USA.

AKÇELIK, R. (2004). **Roundabouts with Unbalanced Flow Patterns**. *ITE 2004 Annual Meeting*, Lake Buena Vista, Florida, USA, Aug 2004.

AKÇELIK, R. (2005). **Roundabout Model Calibration Issues and a Case Study**. Paper presented at the *TRB National Roundabout Conference*, Vail, Colorado, USA, May 2005.

AKÇELIK, R. (2008). **The relationship between capacity and driver behaviour**. Paper presented at the National Roundabout Conference, Transportation Research Board, Kansas City, MO, USA.

AKÇELIK, R. (2009). **Evaluating Roundabout Capacity, Level of Service and Performance**. Paper presented at the ITE 2009 Annual Meeting, San Antonio, Texas, USA.

AKÇELIK, R. (2011). **Some common and differing aspects of alternative models for roundabout capacity and performance estimation**. Paper to be presented at the TRB International Roundabout Conference, Carmel, Indiana, USA. *This paper will be made available after the conference.*

The papers by the author listed above and the REFERENCES section are available for download from **www.sidrasolutions.com**.

THEORETICAL OR EMPIRICAL?

The suggestion heard frequently about roundabout models that "the British model is EMPIRICAL and the Australian model (SIDRA) is THEORETICAL" is based on a widespread misconception promoted on various websites. The difference between the UK TRL regression model and the SIDRA INTERSECTION model is not between an empirical model and a theoretical model but between "**a model not based on any traffic theory (purely empirical)**" and "**a model BASED ON gap-acceptance theory (but still empirical)**". The SIDRA gap-acceptance model parameters are based on empirical models derived from a large database of roundabout survey results.

If the SIDRA INTERSECTION model is theoretical, MICROSIMULATION models are also theoretical. But instead, it is more accurate to state that the analytical SIDRA INTERSECTION model and the microsimulation models are BASED ON traffic flow theory. For example, car-following theory is one of the important elements of microsimulation models. In a particular microsimulation software package, the parameters of the car-following algorithms can be based on empirical studies or can be based on guesswork! Application of the car-following method to different traffic environments and different traffic conditions (e.g. cruising vs queue discharge) is an important issue. Direct observation of driver car-following behaviour and the associated speed-flow relationships based on car-following theory are relevant (vast literature exists on this).

An analogy: A researcher may develop a linear regression model based on observation of speeds and volumes on a freeway or highway. This model may be based on statistical (regression) techniques without any basis in traffic theory. The statistical techniques may be used to prove that the relationship is linear for the particular data set. It is then a purely empirical REGRESSION model. Instead, the researcher may use the same field data to calibrate a non-linear speed-flow relationship based on car-following theory. The resulting model is not purely theoretical or purely empirical. It is based on traffic flow theory and it is empirical. This analogy may help to explain the difference between the existing roundabout models.

Implementation and continued success of modern roundabouts in the USA, as in many countries around the world, depend on improved understanding of major factors that affect the operation of roundabouts. Like all other traffic control devices, the road and intersection geometry, driver behavior, light and heavy vehicle characteristics, behavior and requirements of other road users, traffic flow characteristics and operation of traffic control to resolve vehicle to vehicle conflicts (as well as vehicle to pedestrian conflicts) are important factors that influence roundabout performance. Vehicle traffic flow characteristics represent collective behavior of vehicles in a traffic stream as relevant to, for example, car following, queue forming and queue discharge conditions.

The control rule at modern roundabouts is the yield (give-way) rule. Analytical and microsimulation models use gap-acceptance modeling to emulate behavior of entering drivers yielding to circulating vehicles, i.e. finding a safe gap (headway) before entering a roundabout. This behavior is affected by roundabout geometry (size, entry and circulating lane widths, entry angle, approach and circulating lane arrangements, etc.) which influences such important parameters as sight distance, speed and lane use. The headway distribution of vehicles in the circulating stream (influenced by queuing on the approach road and effective use of circulating lanes at multi-lane roundabouts) is the controlling variable that determines the ability of approach vehicles to enter the circulating road. This is as important as the critical gap (headway) and follow-up headway parameters of the entry stream in determining roundabout capacity, performance (delay, queue length, number of stop-starts, fuel consumption, emissions, and operating cost) and level of service.

Thus, complex interactions among the geometry, driver behavior, traffic stream and control factors determine the roundabout capacity and performance. The level of traffic performance itself can influence driver behavior, increasing the complexity of modeling roundabout operations.

For the practitioner, it is important to understand the reasons behind systematic differences between estimates from different models so that judgment can be made about accepting or rejecting results of a particular model, or a given model can be calibrated, in a specific situation.

Discussion on roundabout models appears to concentrate on capacity alone without much discussion of performance (delay, queue length, emissions, etc). **A simplistic view of roundabout capacity models considers analytical models only, and classifies them into two mutually exclusive categories, namely "theoretical (gap-acceptance) only" and "empirical only".** This view presents the US Highway Capacity Manual and Australian (SIDRA INTERSECTION, AUSTROADS, NAASRA) gap-acceptance based models *(1-12)* as belonging to the first group and a linear regression model developed by UK TRL *(13-19)* as belonging to the second group. As the use of roundabouts became more common in the USA, this narrow view resulted in some controversy as competing software packages based on the two categories, namely SIDRA INTERSECTION representing the gap-acceptance methodology and the ARCADY and RODEL representing the TRL linear regression model, presented significant differences in some cases *(10,20-22)*. The issue, while narrowly focused, has been discussed widely among traffic engineering professionals in the USA *(23, 24)*, and has already been a subject of debate among researchers and practitioners *(25-30)*. The author has presented various thoughts about the limitations of the Australian gap-acceptance models as well as the UK linear regression model previously *(10,22)*.

In fact, the difference is between a *linear regression* model and a *gap-acceptance based* model not between an *empirical* and a *theoretical* model. The current Australian and US HCM models based on gap-acceptance modeling do have an empirical base *(4,6)*. The *Australian* gap-acceptance model *(7,8,10,11)* uses gap-acceptance parameters calibrated by field surveys conducted at a large number of modern roundabouts in Australia *(6)*. *Table 1* shows a summary of field data at 55 roundabout lanes used for calibrating the Australian gap-acceptance based capacity and performance models.

There are significant differences between various gap-acceptance models, e.g. a model that uses fixed gap-acceptance parameters *(1,5)* and another model that determines gap-acceptance parameters as a function of roundabout geometry and traffic flow conditions using empirical relationships *(6-8,12)*. Similarly, there is no reason why a linear regression model could not be based on a lane-by-lane *(12,29,30)* or lane group *(1)* approach and include other parameters related to driver behavior rather than treating all traffic using the approach road as a whole and being limited to roundabout geometry parameters only *(13-19,29,30)*. Thus, it is necessary to investigate the available models in a general framework, considering all aspects of models relevant to roundabout operation. **Microsimulation models** should be included in this general framework of discussion since most modeling issues relevant to analytical models are relevant to microsimulation models as well *(31)*. Comparisons of capacity and performance estimates from different microsimulation models and between microsimulation and analytical models are also recommended.

Table 1 - Summary of field data at 55 roundabout lanes used for calibrating the Australian gap-acceptance based capacity and performance models (points not used in critical gap and follow-up headway regressions not included)

Metric Units

	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

US Customary Units

	Total entry width (ft)	No. of entry lanes	Average entry lane width (ft)	Circul. width (ft)	Inscribed Diameter (ft)	Entry radius (ft)	Conflict angle (°)
Minimum	12	1	10	21	52	13	0
Maximum	41	3	18	39	722	∞	80
Average	27	2	13	31	183	128	29
15th percentile	21	2	11	26	93	33	0
85th percentile	34	3	15	39	230	131	50
Count	55	55	55	55	55	55	55

Figure 1 - An example of dominant entry flow at a modern roundabout in Australia (photo modified for driving on the right-hand side of the road)

PRIORITY SHARING AND PRIORITY EMPHASIS

An important factor that influences the capacity and performance of entry stream is the origin-destination pattern of arrival (demand) flows as related to the approach and circulating lane use (see *Figure 1*). This impacts headway distributions of circulating streams, and as a result, affects approach lane capacities and performance. This factor is not taken into account in the UK TRL linear regression model, the HCM and the Australian gap-acceptance models other than SIDRA INTERSECTION, or any other regression or gap-acceptance models known to the author. Various case studies of unbalanced flows have been reported by the author in previous publications *(10,20-22,32)*.

The limited-priority method of gap-acceptance modeling described by Troutbeck and Kako *(33-35)* allows for priority sharing between entering and circulating vehicles in order to introduce an adjustment 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. The limited-priority adjustment *reduces* the capacity estimated by the absolute-priority method.

The O-D factor used in the SIDRA INTERSECTION roundabout capacity model incorporates the effect of *priority sharing* in adjusting the roundabout capacity function. The O-D factor in SIDRA INTERSECTION 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. 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.

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 SIDRA INTERSECTION 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*, any method based on gap-acceptance modeling with or without limited-priority process, or any comparable empirical method, fails to provide satisfactory estimates of roundabout capacity with unbalanced flows as shown by many case studies.

CALIBRATING SIDRA INTERSECTION FOR LOCAL CONDITIONS

Model calibration is important for the applicability of a given model to different local conditions, and for accommodating changes in driver characteristics over time.

SIDRA INTERSECTION provides powerful model calibration facilities. Intersection-level or approach-level calibration using **Environment factor**, movement-level calibration using **Follow-up Headway** and **Critical Gap** parameters, and the **Sensitivity Analysis** facility can be carried out to achieve observed capacity values.

Research on US roundabouts (NCHRP 3-65, HCM 2010) indicated lower capacity rates at US roundabouts compared with both Australian and UK conditions (even compared with the HCM 2000 capacity model for single-lane roundabouts). This research showed the importance of driver behavior on roundabout capacity. As a result, the HCM version of SIDRA INTERSECTION uses a default Environment Factor of 1.2 to match the lower capacity estimates based on the findings of research on US roundabouts. This is additional to the HCM 2010 model option in SIDRA INTERSECTION which implements the method described in HCM 2010 with many extensions. The HCM 2010 model in SIDRA INTERSECTION can be calibrated for local conditions or for future driver behavior using the relevant parameters provided in the software.

A method has been described for calbrating the UK TRL model by adjusting the capacity at zero circulating flow (y-intercept) value of the linear regression capacity function (15). However, the method has been shown to be problematic (43) since the **capacity decreases with improved geometry (increased entry radius, decreased entry angle, increase entry width, increased flare length) if the capacity at zero circulating flow is user-specified**. This is counter-intuitive as one would expect better capacity values for higher design roundabout design features.

COMPARING ALTERNATIVE MODELS

The discussion about "gap-acceptance" vs "empirical" models for estimating capacity of roundabouts has often been expressed in terms of alternative software packages, although the debate is essentially about alternative capacity models. There are many alternative gap-acceptance and "empirical" models around the world, but unfortunately the controversy has concentrated on "SIDRA" vs software packages that implement the UK TRL linear regression model.

Continuous assessment of existing capacity models in the light of real-life experience of practicing engineers and planners should be encouraged for further improvement of our knowledge in this area, as in other areas of science and technology.

In SIDRA INTERSECTION, several models are available for comparison with the capacity estimates from the SIDRA INTERSECTION gap-acceptance model on a case-by-case basis. In addition to full implementation of the **HCM 2010** model, various linear regression and gap-acceptance capacity models are also included in SIDRA INTERSECTION (**FHWA 2000**, **German**, old Australian **NAASRA 1986**, and **HCM 2000** models).

Case-by-case evaluation of results from alternative models is the best way of helping software users who wish to understand the differences between these models. However, various general notes are included in the following pages.

Refer to detailed case studies given in the papers listed in the INTRODUCTION section.

ROUNDABOUT CAPACITY AND PERFORMANCE MODELS

Firstly, the "**capacity**" and "**performance**" (delay, queue length, stops) models should not be considered in isolation from each other. The emphasis should be on complete methodology with consistency in modeling capacity and performance of not only roundabouts but all intersection types.

Secondly, all relevant fundamental aspects of capacity and performance modeling should be identified to avoid a narrow focus on capacity equations. **Distinguishing alternative methodologies in terms of aggregation levels, i.e. the use of approach flows (UK TRL method), lane groups (HCM method) or lane-by-lane analysis (SIDRA INTERSECTION method), is a more important task for determining the accuracy levels of capacity and performance models, irrespective of them being "empirical" or "gap-acceptance based".**

Thirdly, a satisfactory method for predicting capacity and performance of roundabouts should include modeling of both

- **Driver Yield Behaviour** and
- **Roundabout Geometry**.

The model used in SIDRA INTERSECTION satisfies both criteria using a gap-acceptance based method to model driver yield behaviour, at the same time allowing for the effects of geometric variables. The UK TRL linear regression model allows for only the geometric variables.

ROUNDABOUT MODEL USE IN THE USA

A survey of US traffic professionals at the Roundabout Conference in Seattle WA in May 2000 indicated that SIDRA INTERSECTION is by far the most popular roundabout analysis tool in the USA. SIDRA INTERSECTION use in the USA has increased significantly since then. In March 2010, there were about **2400 licences** of the latest versions of SIDRA INTERSECTION in use in the USA and Canada. Therefore the SIDRA INTERSECTION model has been tested for a long period for its applicability to US traffic conditions.

The ***SIDRA Standard*** model in the SIDRA INTERSECTION software has been used by majority of users to date. With the introduction of the ***HCM 2010*** model as the default option in the US HCM versions of SIDRA INTERSECTION, this trend may change. Detailed discussions on this are presented in recent papers *(47-50)*. Various quotes from earlier US publications are given below.

The **US Florida Roundabout Guide** *(36)* states:

" Several methods of roundabout modeling have been developed, most of them in other countries where roundabouts are common intersection treatments. The Australian methods are most comparable with HCM methods, and are implemented in software that is most compatible with the computational structure that has been developed in Florida for comparing other control modes. For example, the SIDRA program offers an option to implement the HCM procedures for many computations. SIDRA is used in the Florida Roundabout Guide as the primary model for evaluating roundabout performance. ... Like all of the other evaluation models, SIDRA has its own data entry and editing capability. Its user interface is graphics based, and is very well documented and user-friendly. "

Modern Roundabout Practice in the United States *(23)* states:

"There are two primary capacity methods and software programs used in the United States: the Australian method with the SIDRA software and the British method with either the RODEL or the ARCADY software. ... SIDRA appears to be the most commonly used in the United States. This is in line with the fact that two-thirds of the survey respondents mentioned that they followed, or at least consulted, the Australian guidelines for roundabout design. ... "

In **Establishing Roundabout Guidelines for a State DOT, Kinzel** *(24)* writes:

"After much discussion, the technical committee (of the Missouri Department of Transportation) decided that ... aaSIDRA would be the required software for detailed operational analysis. The SIDRA software's increasing prevalence of use in the United States, and the committee's comfort level with a gap-acceptance-based analysis approach, were key factors in this decision."

Maryland DOT Roundabout Design Guidelines *(37)* states:

"Until more data is gathered concerning the performance of roundabouts in Maryland, the Maryland State Highway Administration recommends that designers use the Australian practice at this time. ... This section provides an analytical technique which can be expected to give quite accurate results which reflect current Australian experience and practice. SIDRA software is recommended and is available from McTrans at the University of Florida."

Oregon DOT Research Document on Modern Roundabouts *(38)* suggests:

"Currently, three major software packages from other countries are used to analyze or design roundabouts: SIDRA, ARCADY, and RODEL. Recently, a test of the SIDRA program in the US environment found agreement between SIDRA delay output and collected field data at low volume. The RODEL package has been used to design roundabouts in the US. However, there has been no study or information on the ability of this program to predict roundabout performance in the US."

LESSONS LEARNED FROM US RESEARCH ON ROUNDABOUTS

There are some important aspects of the HCM 2010 roundabout capacity model resulting from research on US roundabouts as presented in the NCHRP Report 572 *(1,41)*. This research confirmed that:

- although important, roundabout geometry *alone* (as in the UK TRL model) is not sufficient for modeling capacity of roundabouts, and
- the model must also include driver behavior parameters (as in the Australian method).

The NCHRP Report 572 found the driver behavior is "*the largest variable affecting roundabout performance*" although "*geometry in the aggregate sense (number of lanes) has a clear effect on the capacity of a roundabout entry*".

The NCHRP Report 572 recognized the importance of lane-by-lane modeling of roundabouts, as the key aspect of the impact of roundabout geometry on capacity, and found that "*the fine details of geometric design (lane width, for example) appear to be secondary and less significant than variations in driver behavior at a given site and between sites*".

This confirms the basic premises of the SIDRA INTERSECTION method, and is in sharp contrast with the UK TRL method. It should be noted that all these methods are "empirical", but differ on identifying key elements of real-life processes that should be included in modeling roundabout capacity.

An important aspect of the ***HCM 2010*** roundabout capacity model is that it is a **lane-by-lane** model consistent with the *SIDRA Standard* model. It is unique in HCM 2010 in the sense that HCM models for other intersection types are by **lane groups**. This also differs from the UK empirical (linear regression) model which treats roundabouts by **approach** without lane group or lane-by-lane level of detail. Modeling an intersection lane-by-lane, by lane groups and by approaches indicate an increasing level of model coarseness.

The HCM 2010 roundabout capacity model can be viewed as a non-linear empirical (regression) model with a theoretical basis in gap-acceptance methodology.

The HCM 2010 exponential regression model is in fact a gap-acceptance model which uses the form of ***Siegloch M1*** gap-acceptance model *(46)*. HCM 2010 and NCHRP 572 accept that the exponential regression model has a gap-acceptance basis but they do not identify it as the Siegloch M1 model. *M1 model* refers to the assumption of random arrivals of vehicles with no bunching. Derivation of the Siegloch M1 model from the bunched exponential distribution of headways used in the SIDRA Standard model, and detailed information about the capacity models and assumptions about arrival headways (random or bunched) can be found in a paper by the author *(46)*.

The NCHRP Report 572 also showed that the capacity model using exponential regression and using the model parameters derived from average field values of the gap-acceptance parameters t_f and t_c are very close. Thus modeling capacity by a gap-acceptance method (using t_f and t_c parameters determined in the field in a "theoretical" gap-acceptance equation) and modeling capacity by direct regression using field capacities give very close results. **This confirms the validity of gap-acceptance methodology for roundabout capacity modeling.**

MODEL COMPARISON

Figures 2a and 2b present comparison of the following capacity estimates for a single-lane roundabout example:

- **SIDRA INTERSECTION**
- **UK TRL linear regression, and**
- **HCM 2010 single and multi-lane models.**

A moderate Origin-Destination flow pattern effect (balanced flows) represented by an O-D Factor of 0.85, and Medium level of adjustment for the ratio of entry lane flow rate to circulating flow rate were assumed for SIDRA INTERSECTION.

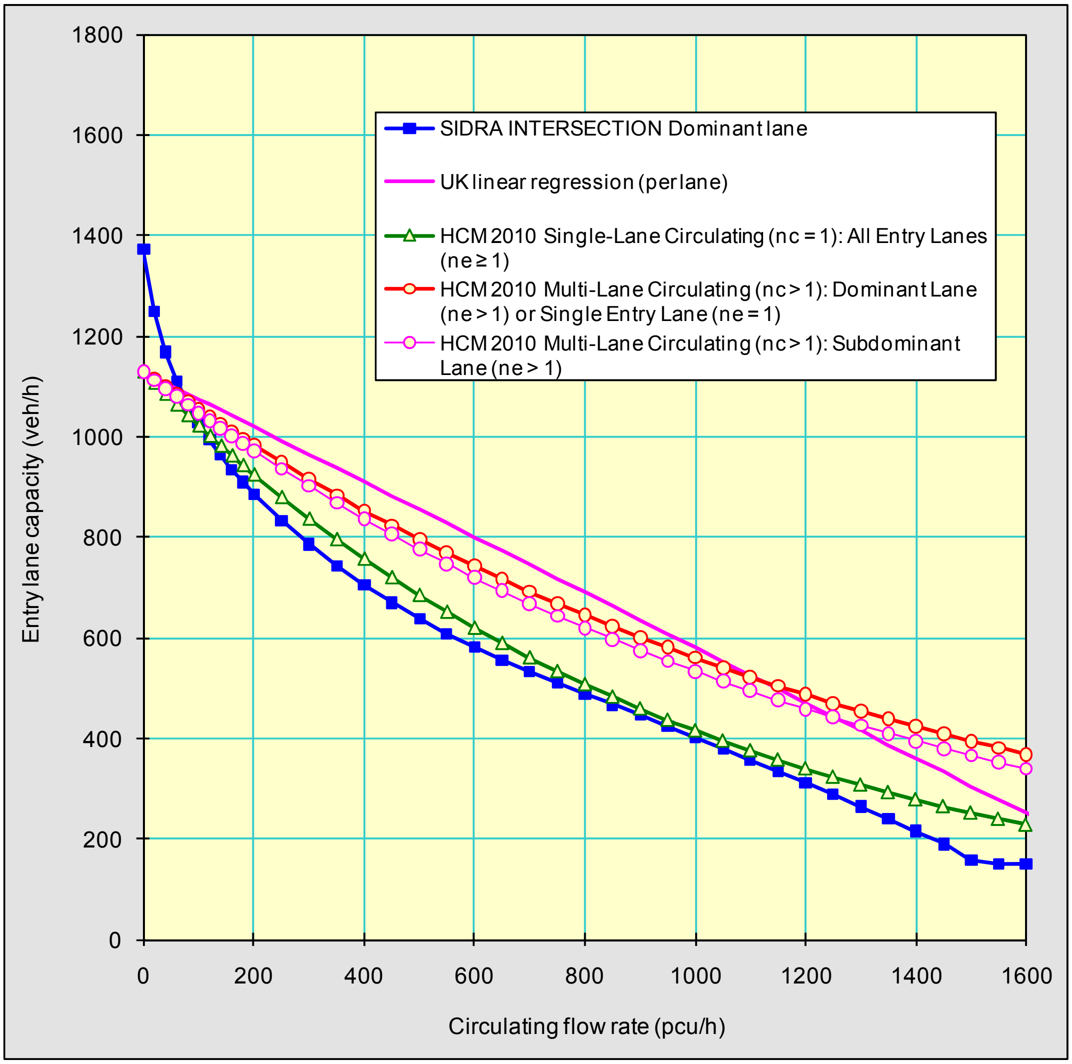
The results shown in *Figure 2a* are based on models ***calibrated for US conditions***:

- For the SIDRA INTERSECTION model, Environment Factor = 1.2 (default value) was used.
- For the UK TRL model, the y intercept was set as 1130 which is the value used by the HCM 2010 model.

For this example, it is seen that the UK TRL model overestimates capacity compared with other models (the results are closer to the HCM 2010 multi-lane results).

The SIDRA standard model results are seen to be very close to the HCM 2010 model results except at very low circulating flows where the capacity curve can vary according to the level of adjustment chosen for the ratio of entry flow to circulating flow.

In *Figure 2b*, the ***non-calibrated*** SIDRA INTERSECTION and UK TRL models are compared for the same example (Environment Factor = 1.0, y intercept not set). This example represents the general trend of difference between these two models: the UK TRL model estimates are lower for low circulating flow rates and higher for medium to high circulating flow rates. Reasons for this trend are discussed below.



Capacity at zero circul. flow (for UK TRL)	No. of entry lanes	No. of circ. lanes	Inscribed diameter	Entry radius	Entry angle	Entry lane width	Total entry width	App. half width	Flare length (eff.)
A	n_e	n_c	D_i (m)	r_e (m)	Φ_e (deg)	w_L	w_e (m)	w_a (m)	L_f (m)
1130	1	1	36	20	30	4.0	4.00	3.50	20

Figure 2a - Model comparison (single-lane roundabout example): calibrated models

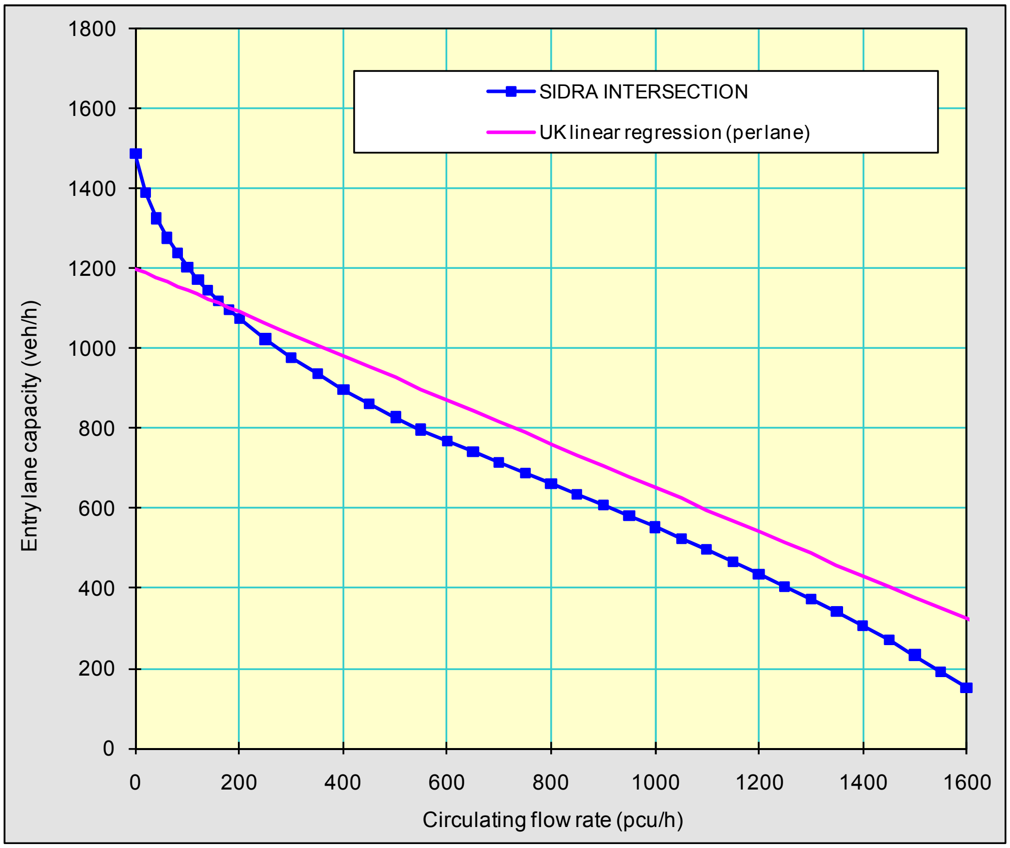


Figure 2b - Model comparison (single-lane roundabout example): non-calibrated models

COMMENTS ON MODEL DIFFERENCES

Possible reasons for the UK TRL Linear Regression model to give **lower capacities at low circulating flows and higher capacities at high circulating flows** as seen in *Figure 2b* 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.

UK TRL Linear Regression Model Capacity Estimates: Low Circulating Flow Rates

With the UK TRL 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 appears to be biased since it seems 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 UK TRL 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 3* indicate that relative frequencies of data at circulating flows below 600 pcu/h were very small *(17,18)*. This is likely to be similar for the overall database used in deriving the TRL Linear Regression model for at-grade roundabouts *(15)*. These examples also show how the "observed regression line" can underestimate capacity at low circulating flows. In *Figure 3(b)*, the broken line representing the TRL 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 *(18)*.

For the combined "high entry lane flow and low circulating flow" conditions, the SIDRA INTERSECTION model implies alert drivers with small reaction times (around **1 second**) whereas the TRL Linear Regression and HCM 2000 models imply relaxed drivers with large reaction times (**around 2 seconds**), accepting to wait in a long queue in congested conditions in spite of very large gaps available in the circulating stream *(22)*.

UK TRL Linear Regression Model Capacity Estimates: High Circulating Flow Rates

Contrary to the low circulating flow region, the TRL 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 research leading to the linear regression model was preoccupied with the effect of roundabout geometry:

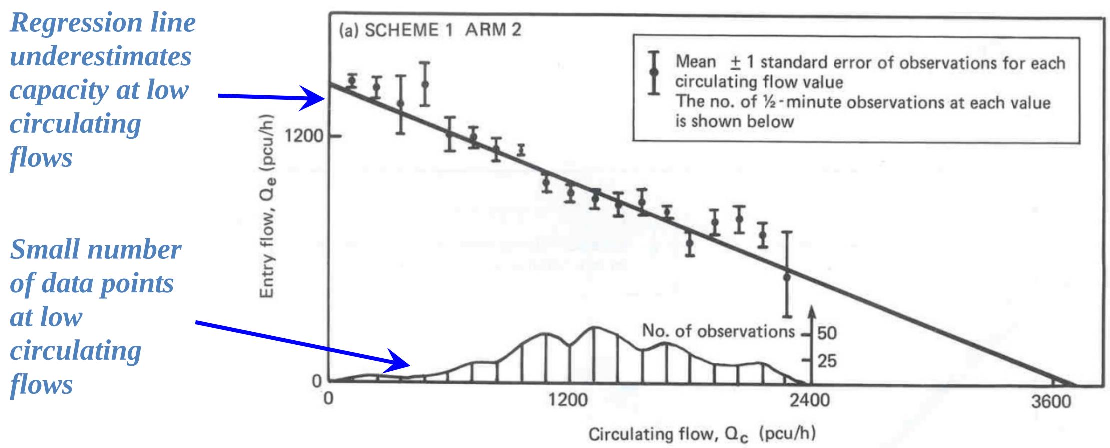
> "*The intention was to provide a single method for estimating the capacity of entries to all at-grade roundabouts. The unified formula was developed using observations made on the TRRL Test Track and at a large number of public road sites; these observations covered a wide range of values of those geometric parameters which were found to affect the entry capacity.*" *(18 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.*" *(15 p.3)*.

Examples of the two design types used in capacity measurements for the UK TRL Linear Regression model discussed in the above quote are shown in *Figure 4* *(17)*. 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 UK TRL 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 *(10 Section 7.4.2)*.

The approach-based method adopted for the UK TRL Linear Regression model was an improvement over the method that existed then, which estimated capacity of the roundabout as a whole. 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 UK TRL Linear Regression model *(29,30)*.

(a) At-grade roundabout in Wincheap, Canterbury, UK (17)



(b) Grade-separated roundabout in Bradford, UK (18)

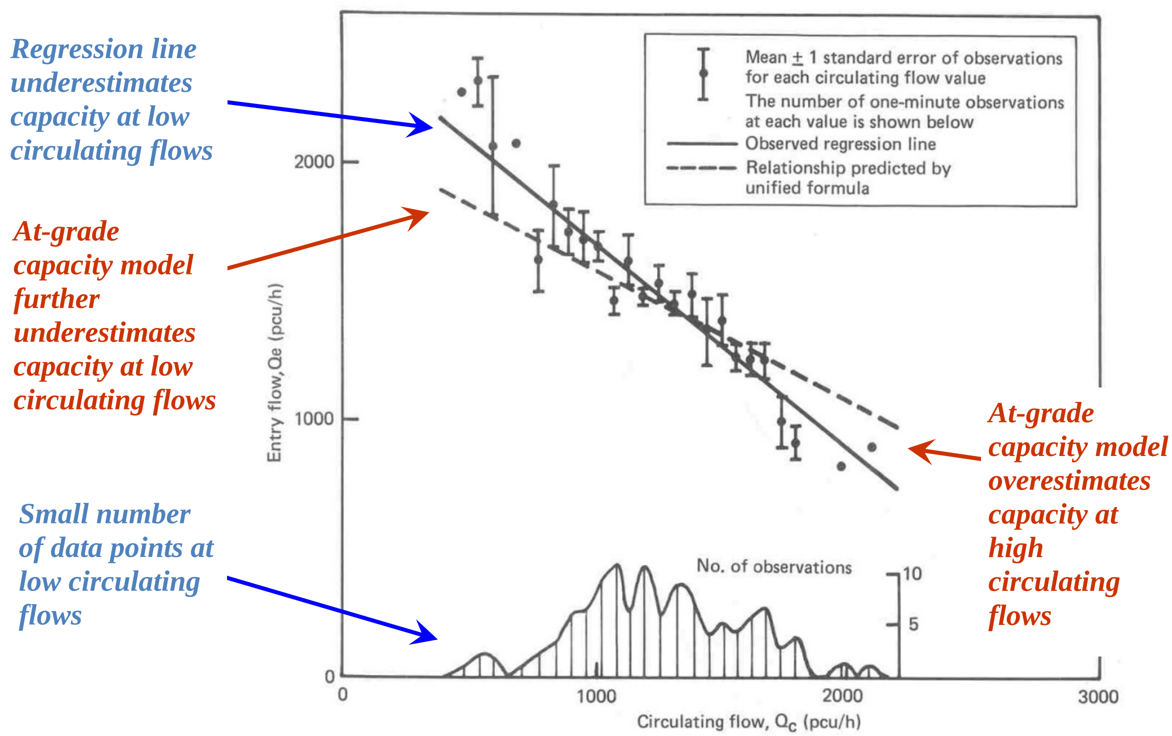


Figure 3 - Data from roundabout capacity surveys at UK roundabouts

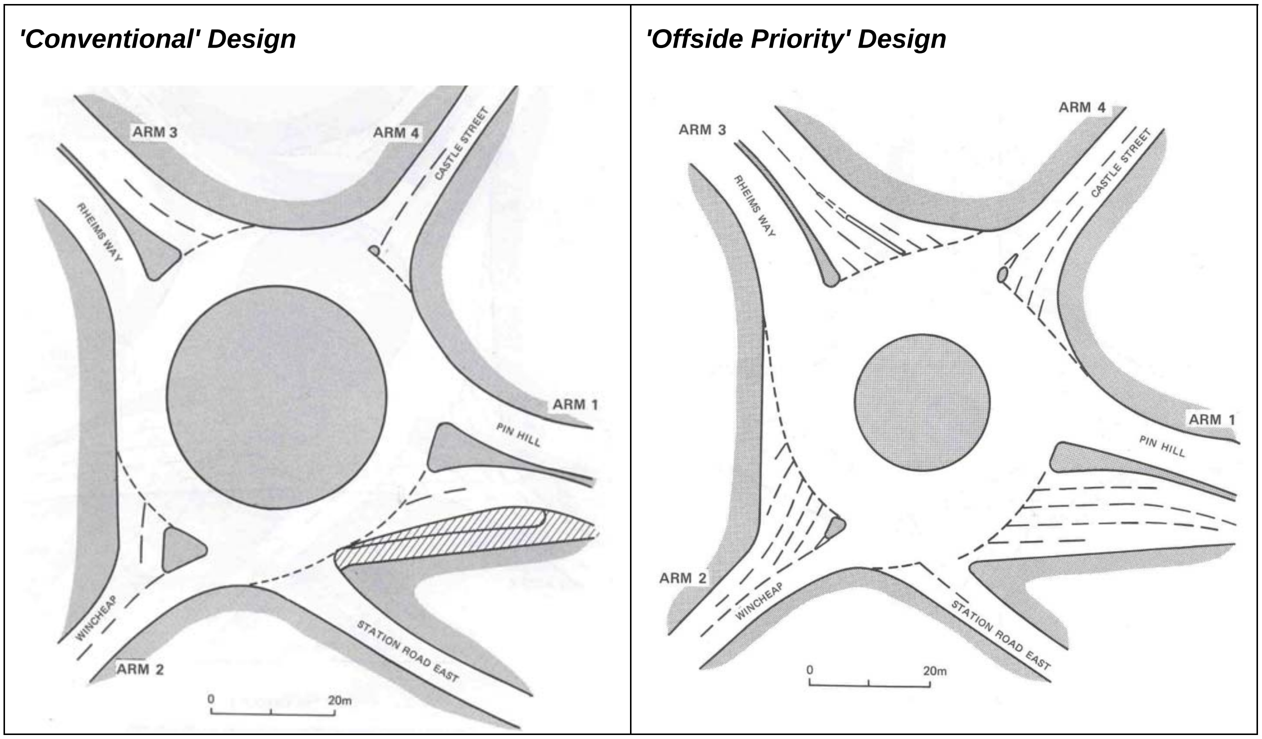


Figure 4 - Examples of 'Conventional' and 'Offside Priority' roundabout designs used in capacity measurements for TRL linear regression model (17)

As seen in *Figure 4*, a highly flared offside priority design means a significantly increased number of entry lanes (this would be modeled as short lanes in SIDRA INTERSECTION). 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 ∞) would encourage merging behavior and possibly induce priority reversal at high circulating flow rates (see *Table 1* for the entry angle and turn radius values in the Australian database). 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** *(14 p.4 and 15 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 regression model.

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 *(15,26,28)*. These concerns appear to have resulted from the geometric design features adopted at roundabouts included in the UK roundabout capacity surveys. See the discussion on this matter at the start of this document.

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 3(b)*). Semmens *(18 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 *(18 p.10)* indicates that these roundabouts had negligible or no flaring *(18 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 *(18 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 UK TRL Linear Regression model reflects the conventional and offside-priority designs used in that country at the time, which seem to have encouraged merging behavior.** It is believed that these roundabout designs are not representative of modern roundabout designs adopted in Australia *(8)* and the USA *(23,36-40)*, whose approaches are more like the unflared entries at *grade-separated* roundabouts discussed by Semmens *(18)*.

Pattern of Difference Between the SIDRA INTERSECTION and the UK TRL Linear Regression Models

Our comparisons of the two models using the SIDRA INTERSECTION package to date indicate that while the two models tend to agree for medium demand flow rates (around 600-900 veh/h) with balanced origin-destination demand flow patterns, there are **significant differences for low and high circulating flows, especially with unbalanced origin-destination patterns**. All case studies with such conditions we have looked at indicate that SIDRA INTERSECTION estimates represent real-life conditions reasonably well.

The following is a risk analysis of design implications of the differences between the two models.

1. LOW CIRCULATING FLOWS

SIDRA INTERSECTION capacity estimates are HIGHER

	Design by UK TRL model	**Design by SIDRA INTERSECTION**
If SIDRA INTERSECTION model is correct	UK TRL model may impose a **capacity constraint** when the demand flow rate is high against a low circulating flow rate. This may cause over-optimistic estimate of the capacity of the next entry. The method **may fail to predict poor performance of the next entry** under such unbalanced flow conditions.	**OK**
If UK TRL model is correct	**OK**	**Many real-life cases support the SIDRA INTERSECTION case.**

2. HIGH CIRCULATING FLOWS

The UK TRL model capacity estimates are HIGHER

	Design by UK TRL model	**Design by SIDRA INTERSECTION**
If SIDRA INTERSECTION model is correct	May cause under-design (resulting in high degrees of saturation).	**OK**
If UK TRL model is correct	**OK**	**Many real-life cases indicate that roundabout performance deteriorates quickly as the demand flow rates increase. This is partly due to the increasing impact of unbalanced flow conditions at high flow rates.**

Advantages of Using SIDRA INTERSECTION

- SIDRA INTERSECTION uses a **lane-by-lane analysis** method with an advanced gap-acceptance model of the “yield” behaviour of drivers at modern roundabouts.
- **SIDRA INTERSECTION model does not present problematic aspects of the UK TRL model in relation to decreased capacities for improved geometric parameters when the y intercept is fixed for calibration purposes.**
- You can use the **parameter sensitivity** facility of SIDRA INTERSECTION to obtain graphs of how capacity and a large number of performance parameters (delay, queue length, cost, etc) change with roundabout geometry and driver behaviour (gap-acceptance parameters).
- Unlike the UK TRL linear regression method, the SIDRA INTERSECTION gap-acceptance method is **consistent with the US Highway Capacity Manual**.
- SIDRA INTERSECTION includes the **HCM 2010 roundabout capacity model**, and also presents results from additional roundabout capacity models including the FHWA 2000 model, and German linear regression and gap-acceptance models.
- SIDRA INTERSECTION provides results for alternative models for the purpose of **model comparisons.**
- SIDRA INTERSECTION will help you with comparing **alternative intersection treatments** (roundabouts, actuated and pretimed signals, sign control) in one package.
- SIDRA INTERSECTION provides estimates of **operating cost, fuel consumption, CO_2, other emissions** to enable the user to demonstrate benefits of alternative intersection treatments and improvements to existing intersection conditions in a more powerful way.

The rest of this document presents more detailed points about the SIDRA INTERSECTION and the UK TRL Linear Regression Models.

Geometric Parameters in the SIDRA INTERSECTION and UK TRL Models

In the SIDRA INTERSECTION roundabout capacity model, gap acceptance (driver behaviour) parameters are related to:

- roundabout geometry << *in the UK TRL model*
- circulation flow rate << *in the UK TRL model*
- entry flow rates << *NOT in the UK TRL model*

Therefore, past criticism of gap-acceptance models that use constant critical gap and follow-up headway **is not relevant** to the SIDRA INTERSECTION method.

Geometric factors affecting capacity through gap acceptance parameters in SIDRA INTERSECTION:

- **Inscribed diameter** << *in the UK TRL model*
- **Entry radius** << *in the UK TRL model*
- **Entry angle** << *in the UK TRL model*
- **Average entry lane width** *the UK TRL model uses*
- **Number of entry lanes** *total entry width*
- **Number of circulating lanes** << *NOT in the UK TRL model*

Flared Entries or Short Lanes

SIDRA INTERSECTION and UK TRL models differ in handling flared entries.

In the SIDRA Standard model, approach flaring effects are predicted through the use of entry lane width parameter (extra lane width at the give-way line which is not sufficient for a separate queue to form) and short lane modeling (extra lane width which allows for an additional queue to form).

The short lane model applies to the HCM 2010 model as an important extension. Modeling of short lane capacity is an important part of roundabout capacity modeling since such short lanes (flares) may be very effective in capacity terms at roundabouts. SIDRA INTERSECTION uses a space-based capacity model for short lanes making use of gap-acceptance cycles (blocked and unblocked intervals) to determine excess flows overflowing from short lanes into adjacent lanes.

Since the SIDRA Standard and HCM 2010 models are lane-based, and with the use of short lane models, approach flaring parameters are not needed unlike the UK TRL approach-based linear regression model.

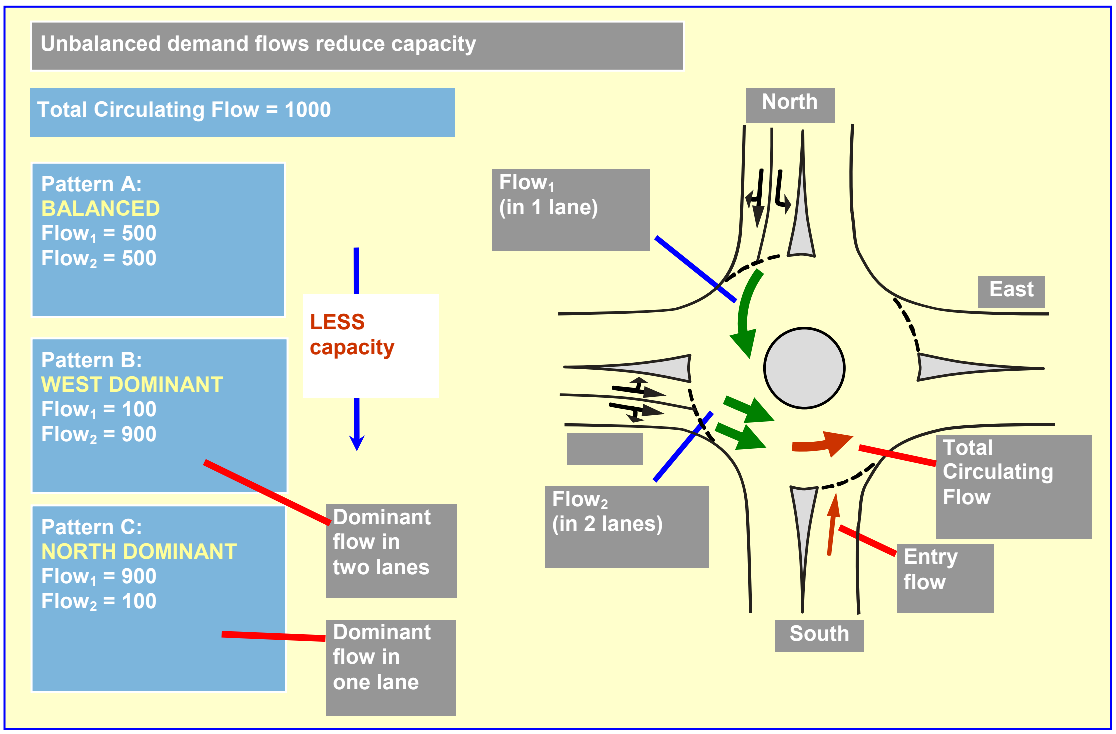
The effectiveness of short lanes depends on flow conditions. Short lanes allocated to turning streams exclusively, or flares on single-lane approaches, do not necessarily reduce the v/c ratio of the approach when the flow rates of traffic using short lanes (flares) are low. Modeling of short lanes (flares) using geometric parameters only can therefore underestimate the degree of saturation (v/c ratio) of the approach.

Parameters in the SIDRA INTERSECTION Model but NOT in the UK TRL model

Effect of origin-destination pattern, proportion queued and lane usage

The SIDRA INTERSECTION 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**. 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. The **UK TRL Linear Regression model does not consider these factors**, and has been found to be too optimistic, i.e. it has failed to predict congested conditions observed at many roundabouts in Australia and the UK.

The effect of the Origin-Destination (O-D) pattern on capacity in modeling unbalanced flows by SIDRA INTERSECTION is shown below



Ratio of entry flow to approach flow

Capacity increases as this ratio increases, but subject to constraints.
UK TRL model predicts low capacities when circulating flow is very low and entry flow is high as discussed in previous pages.

LANE USE: exclusive vs shared lanes and lane underutilisation

A major shortcoming of the UK (TRL) model is lack of **sensitivity to approach and circulating lane use**. See example given in:

CHARD, B. (1997). **ARCADY Health Warning: Account for unequal lane usage or risk damaging the Public Purse!**. *Traffic Engineering and Control*, 38 (3), pp. 122-132.

Approach lane flows

Multi-lane approaches have **unequal lane capacities** for dominant and subdominant lanes; additional lanes add LESS to capacity. The US research has confirmed this feature of SIDRA INTERSECTION based on Australian research.

HEAVY VEHICLES in the circulating stream and entry lane

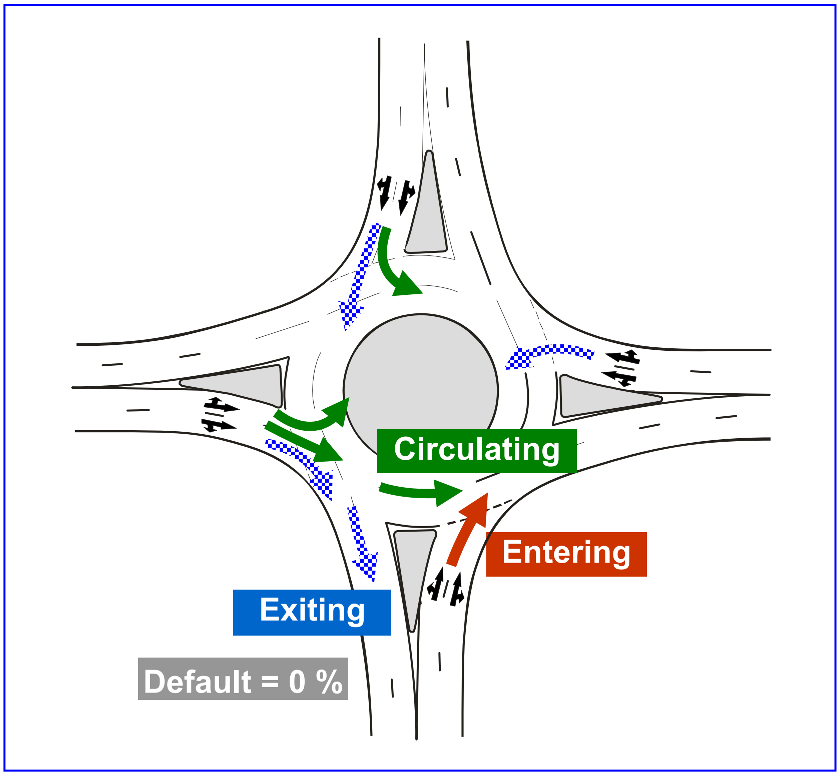
In SIDRA INTERSECTION, heavy vehicles in the circulating stream and entry lane reduce capacity. The effect on the entry stream is allowed for by increased critical gap and follow-up headway values.

EXTRA BUNCHING due to upstream signals

This has effect at medium to high flow conditions.

EXITING FLOW

When exiting flows influence entering vehicles, entry capacity is reduced.



CONCLUSION

You may have heard strong arguments for and against the SIDRA INTERSECTION and UK TRL "empirical" models from different sources (including this document!). We recommend that, if you are not sure, you use alternative models and compare the results on a case-by-case basis.

To facilitate this, alternative models are provided in the SIDRA INTERSECTION software package. These include the **HCM 2010** model, **FHWA 2000** model (based on the UK linear regression model), and **German linear regression** and **gap-acceptance** models.

We suggest that you compare alternative models on a case-by-case basis. Refer to many case studies published by the author (see the selected list of papers given in the INTRODUCTION section).

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