Some common and differing aspects of alternative models for roundabout capacity and performance estimation

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Paper presented at the International Roundabout Conference, Transportation Research Board, Carmel, Indiana, USA, 18-20 May 2011.

ABSTRACT

This paper considers three well-known analytical models of roundabout capacity, and discusses some common and differing aspects of these models. The models considered are the US Highway Capacity Manual 2010 (HCM 2010) model, Australian SIDRA INTERSECTION model and the UK TRL (linear regression) model. These models have some common features as well as significant differences. A detailed table comparing the features of these capacity models is presented. The UK TRL and SIDRA models are compared in relation to several geometric parameters (entry radius, entry angle, inscribed diameter and flaring). Detailed comparison of estimates of capacity and degree of saturation (v/c ratio) produced by these models are presented for a multi-lane roundabout example. The aim of the paper is to enhance understanding of the fundamental aspects of different roundabout capacity models available around the world.

INTRODUCTION

The purpose of this paper is to provide a wide perspective about roundabout capacity models by focusing on three well-known models. These are the SIDRA INTERSECTION model based on research on roundabouts in Australia *(1-4)*, the Highway Capacity Manual (HCM 2010) model based on research on roundabouts in the USA *(5-7)* and the TRL model based on research on roundabouts in the UK *(8-11)*. Developed in different countries at different times, these models have common elements yet significant differences in modeling methodologies.

Both the original SIDRA roundabout capacity model and the HCM 2010 model are implemented in the SIDRA INTERSECTION software. To distinguish the two models, they will be referred to as the *SIDRA Standard* model and the *HCM 2010* model, and it in order to avoid misleading statements about particular software packages, the third model will be referred to as the *UK TRL* model to distinguish it as the original published model from the ARCADY and RODEL software which have implemented it.

General features of these three models will be summarized and the estimates of capacity and degree of saturation (v/c ratio) values obtained from these models will be compared for a multi-lane roundabout example.

For the purpose of comparison with the HCM 2010 model representing driver behavior in the USA, calibrated versions of the *SIDRA Standard* model and the *UK TRL* model will be used. The *SIDRA Standard* model will use a general Environment Factor of 1.2 and the *UK TRL* model will be assigned a value of 1130 as the "capacity at zero circulating flow" (or y-intercept).

There has been much discussion on these models to date. Refer to a detailed paper by the author presenting an assessment of the *HCM 2010* model including comparison of estimates of capacity, degree of saturation (v/c ratio), delay, level of service and queue length for Example Problem 2 given in HCM 2010, Chapter 21 *(3)*.

The author has discussed the *UK TRL* model in a previous publication *(12)* and compared it with the *SIDRA Standard* model with many case study examples in several papers *(12-14)*. A recent paper discussed possible methods to calibrate of the *UK TRL* method to give results closer to the *HCM 2010* model *(15)*.

There are many more models published in the literature. Several additional models such as the FHWA 2000 model and German linear and gap-acceptance models are also implemented in the SIDRA INTERSECTION package. Relationships among roundabout analysis models related to the SIDRA INTERSECTION model, or used in SIDRA INTERSECTION as an additional model, are shown in *Figure 1*.

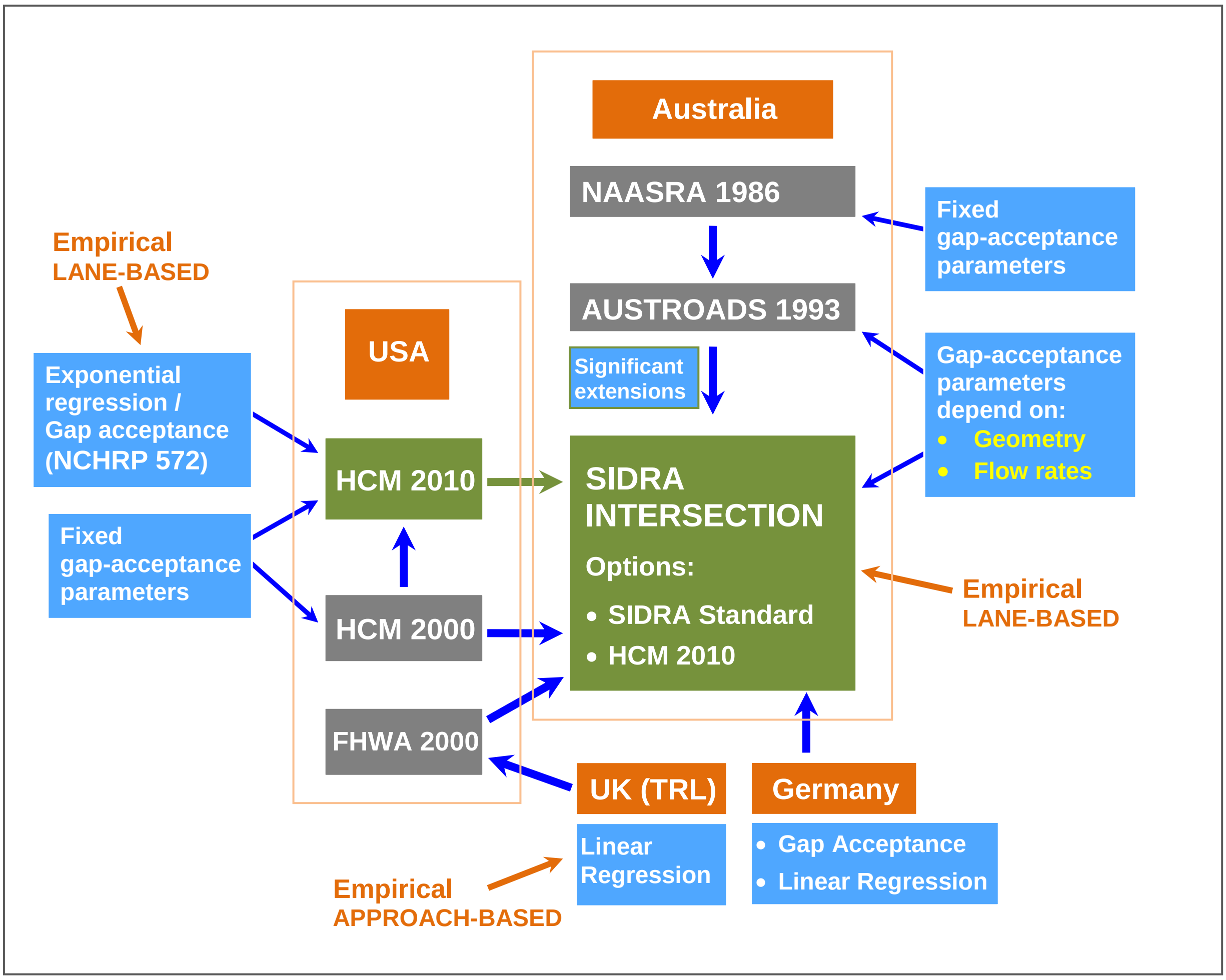

Figure 1 - Relationships among roundabout analysis models used in SIDRA INTERSECTION

In the past, the *SIDRA Standard* model has been referred to as a gap-acceptance model, and the UK *TRL model* has been referred to as an empirical (linear regression) model, and there have been discussions about relative benefits of these modeling approaches as though they are mutually exclusive.

Interestingly, the more recent *HCM 2010* model as a non-linear empirical (exponential regression) model with a theoretical basis in gap-acceptance methodology has shown that a combination of theoretical and empirical approaches is possible.

The author has indicated that the *HCM 2010* exponential regression model uses the form of *Siegloch M1* gap-acceptance model *(3,4,16)*.

The discussion should go beyond simple model categorization, and focus on key aspects of each model related to roundabout geometry and driver behavior affecting capacity estimates. Research on US roundabouts presented in the NCHRP Report 572 *(6)* and formed the basis of the *HCM 2010* model confirmed that although important, roundabout geometry *alone* is not sufficient for modeling capacity of roundabouts, and the model must also include driver behavior parameters.

The NCHRP Report 572 found that:

- 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*",
- lane-by-lane modeling of roundabouts is important as the key aspect of the impact of roundabout geometry on capacity, and
- "*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*".

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 research finding provides a clear confirmation of the validity of gap-acceptance methodology for roundabout capacity modeling. Nevertheless, discussion about sensitivity of capacity to parameters representing roundabout geometry and driver behavior is a useful one.

ROUNDABOUT CAPACITY

Capacity is the maximum sustainable flow rate that can be achieved during a specified time period under given (prevailing) road, traffic and control conditions. Roundabout is an intersection, and like all signalized and unsignalized intersections, its capacity follows the basic capacity formulation for an *interrupted facility,* i.e. it is the maximum queue discharge rate reduced by time lost due to interruption caused by the relevant form of control:

$$Q = s\,u \quad (1)$$

where Q = capacity (veh/h), u = proportion of time when the vehicles can depart from the queue (signals are green or gaps are available in the opposing stream) and s = saturation (queue discharge) flow rate (veh/h).

For signalised intersections, u is the *green time ratio*, u = g / c, where g = effective green time (s) and c = cycle time (s). For gap-acceptance processes at roundabouts and sign-controlled intersections, u is the *unblocked time ratio* related to average durations of block and unblock periods in the opposing stream *(16)*.

Saturation flow rate (s) is the maximum flow rate that can be sustained when there is a queue and the vehicles can depart from the queue, i.e. signals are not red or the gaps in the opposing stream are not too short. Saturation flow rate corresponds to a *queue discharge headway* which represents the minimum headway between vehicles that is achieved while they are departing from the queue:

$$h_s = 3600 / s \quad (2)$$

where h_s = queue discharge (saturation) headway (seconds) and s = saturation flow rate (veh/h).

For example, a saturation flow rate of s = 1800 veh/h corresponds to a saturation headway of h_s = 2.0 seconds.

The gap-acceptance method uses the *follow-up headway* (t_f) as the queue discharge (saturation) headway ($t_f = h_s$). The follow-up headway corresponds to a saturation flow rate which is the maximum gap-acceptance capacity that can be achieved when the opposing flow is close to zero:

$$s = 3600 / t_f \quad (3)$$

where s = saturation flow rate (veh/h) and t_f = follow-up headway as a queue discharge (saturation) headway (seconds).

For example, a follow-up headway of t_f = 3.0 seconds implies a saturation flow rate of s = 1200 veh/h.

The saturation flow rate for a gap-acceptance process is the maximum capacity that can be achieved when the opposing flow is close to zero. In terms of the *UK TRL* model ($Q = A - B\ q_c$), this is the *y intercept*, or "*capacity at zero circulating flow*" (A in the equation). The capacity is reduced from this value with increased opposing flow rates (q_c) due to the decreased values of unblocked time ratio depicted as a non-linear or linear relationship to represent different models in *Figure 2*.

In capacity models based on gap-acceptance modeling, while the follow-up headway determines the capacity value at low opposing flow rates directly, the critical gap parameter affects the u parameter (the proportion of time when the vehicles can depart from the queue) in *Equation (1)* with lower values of u resulting from larger values of critical gap (hence lower capacity) for a given opposing flow rate. This is also depicted in *Figure 2*.

The *UK TRL* model has been identified as having a *fatal flaw* if the value of y intercept (A) is fixed *(15)*: the model will estimate capacity decreases with improved geometry (increased entry radius, decreased entry angle, etc). This results from the increased slope (B) of the linear equation which means a sharper decrease in capacity. When the value of A is estimated freely, increase in the value of A with improved geometry compensates and the capacity value increases with improved geometry. When the value of A is fixed (e.g. in an effort to calibrate the model for local conditions), the capacity will decrease with improved geometry. Similarly, when the value of A is fixed, the capacity will increase with poorer geometry (see depiction of this in *Figure 3*). This can be understood more clearly by inspecting the effect of geometry parameters used by the model on parameters A and B.

Due to the lack of a direct analytical formulation of the relationship between capacity and driver behavior, it is often overlooked that driver behavior (characteristics of driver - vehicle units in traffic) is the main determinant of capacity. Capacity models for roundabouts and two-way sign controlled intersections based on gap-acceptance modeling use follow-up headway and critical gap parameters for entering traffic, and headway distribution parameters for opposing (circulating, or major road) traffic reflecting driver behavior. The author discussed a relationship between saturation headway and driver response time *(3,4,17)*.

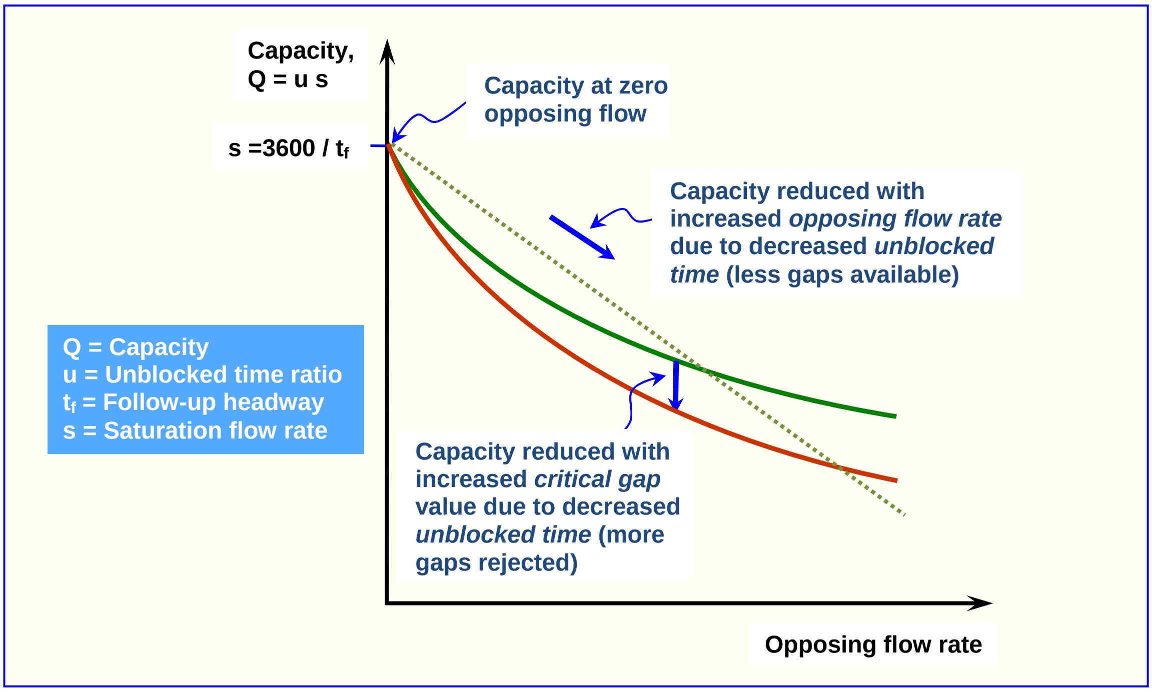

Figure 2 - Roundabout capacity

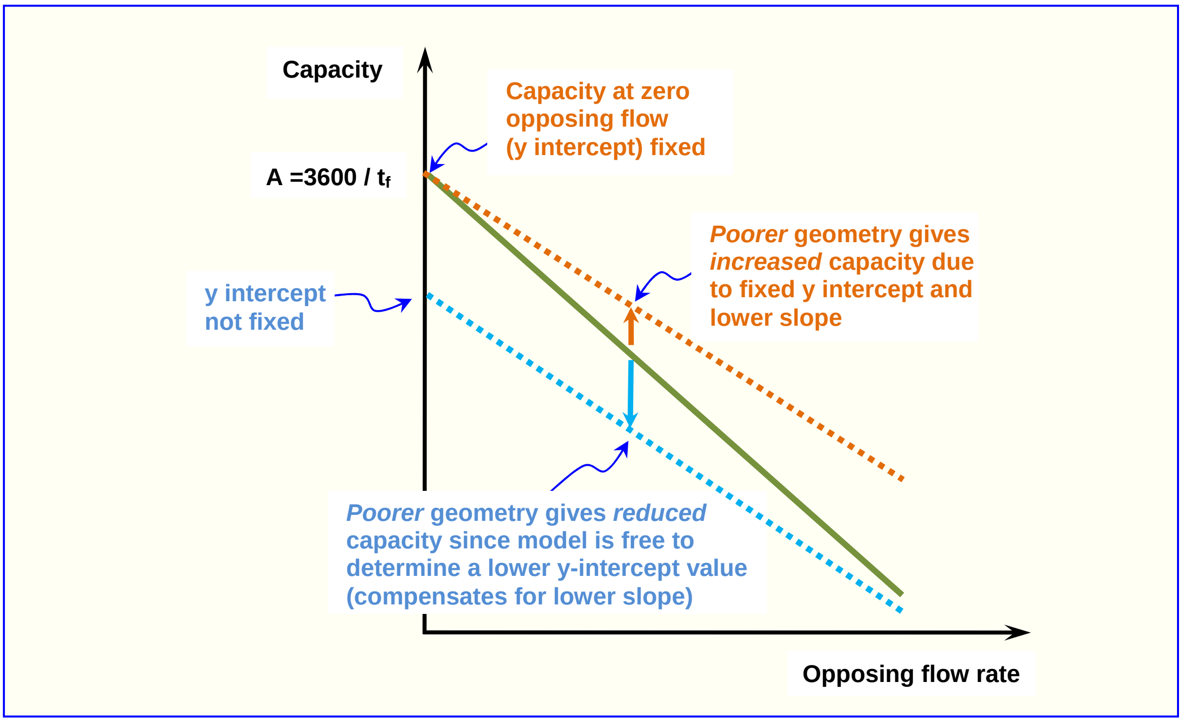

Figure 3 - Problematic nature of the UK TRL model when the y intercept is fixed for calibration purposes

In SIDRA INTERSECTION, the *environment factor* parameter is used indirectly to allow for the effects of such factors as driver aggressiveness and alertness (driver response times), standard of intersection geometry, visibility, operating speeds, sizes of light and heavy vehicles, interference by pedestrians, standing vehicles, parking, buses stopping, and so on (if not modeled explicitly).

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 *(1,18-20)*. It is unique in HCM 2010 in the sense that HCM models for other intersection types are by ***lane groups*** (movements combined according to shared lanes). This also differs from the *UK TRL* model which treats roundabouts by ***approach*** without lane group or lane-by-lane level of detail (all movements in all approach lanes combined). Modeling an intersection lane-by-lane, by lane groups and by approaches indicate an increasing level of model coarseness.

The lane-by-lane method simplifies the analysis method and introduces improved accuracy levels in capacity and performance prediction by allowing improved spatial (geometric) modeling of all types of intersection. This method allows modeling of unequal lane utilization which is an important factor that affects the capacity and performance of roundabouts, including the effect of circulating lane use at multilane roundabouts.

MODEL FEATURES

A brief comparison of the main features of *SIDRA Standard, HCM 2010* and *UK TRL* models is given in *Tables 1a and 1b*. The features include methodology, model level of detail (lane-based or approach-based), parameters used in the model to represent driver behavior and roundabout geometry, and model calibration methods. The comparison focuses on the capacity model and does not cover modeling of performance (delay, queue length, fuel consumption and emissions, etc) and level of service methods used.

Table 1a

Comparison of the main features of *SIDRA Standard*, *HCM 2010* and *UK TRL* models

Model Feature	*SIDRA Standard* Model	*HCM 2010* Model	*UK TRL* model
Methodology	Based-on gap-acceptance theory with empirical (regression) equations to model gap-acceptance parameters.	Empirical (exponential regression) capacity model with clear basis in gap-acceptance theory.	Empirical (linear regression) capacity model with no stated theoretical basis.
Individual Entry and Circulating Lanes	***Lane-based*** model: Capacity and performance of individual entry lanes are modeled.	***Lane-based*** model: Capacity and performance of individual entry lanes are modeled.	***Approach-based*** model: All lanes aggregated and capacity and performance modeled for the approach as whole.
	Variations in lane disciplines (exclusive and shared lanes, slip and continuous lanes) can be modeled.	Variations in lane disciplines (exclusive and shared lanes, slip and continuous lanes) can be modeled.	Variations in lane disciplines (exclusive and shared lanes, slip and continuous lanes) cannot be modeled.
	Dominant and subdominant entry lanes identified.	Dominant and subdominant entry lanes identified.	Entry lanes not identified.
	Number of circulating lanes affects capacity.	Number of circulating lanes affects capacity.	Number of circulating lanes does not affect capacity.
	Circulating lane flow rates used allowing for unbalanced flows. Amount of queuing before entering circulating stream affects capacity.	Total circulating flow rate used. Circulating lane flows not used.	Total circulating flow used. Circulating lane flows not used.
	Assumes bunched arrival headways for the circulating stream. Proportion bunched modeled.	Assumes random arrival headways for the circulating stream.	No explicit assumptions about circulating stream headways.
	Extra bunching to model upstream signal effects allowed.	Effect of upstream signals modeled as an extension in SIDRA INTERSECTION software.	Not applicable.
	A proportion of exiting flow can be added to circulating flow as opposing flow.	Not applicable.	*Not known to the author.*
Lane Utilization for Multilane Approaches	Entry lane flow rates are calculated.	Entry lane flow rates are calculated.	Lane flows cannot be modeled.
	De facto exclusive lanes are identified.	De facto exclusive lanes are identified.	De facto exclusive lanes cannot be identified.
	Unequal lane use can be modeled by specifying lane utilization ratios.	Unequal lane use can be modeled by specifying lane volume percentages.	Unequal lane use cannot be modeled.
Volume / Capacity Ratio	v/c ratio (degree of saturation) for a multilane approach represents the *critical lane* value.	v/c ratio for a multilane approach represents the *critical lane* value.	Only the average v/c ratio for the approach is available. This will underestimate the higher v/c ratio of the critical lane unless equal lane use exists.
Unbalanced Flows	Capacity is sensitive to Origin-Destination demand flow pattern, lane use and level of queuing on approaches.	No sensitivity to Origin-Destination flow patterns. O-D Factor method offered as an extension in SIDRA INTERSECTION software.	No sensitivity to O-D flow patterns.
	Adjustment options exist for high Entry Flow / Circulating Flow ratio (increased entry capacity at very low circulating flow rates due to increased driver aggressiveness level).	Adjustment options for high Entry Flow / Circulating Flow ratio offered as an extension in SIDRA INTERSECTION software.	Not applicable.

Continued in Table 1b

Table 1b

Comparison of the main features of *SIDRA Standard, HCM 2010* and *UK TRL* models (*continued)*

Model Feature	*SIDRA Standard* Model	*HCM 2010* Model	*UK TRL* model
Driver Behavior Parameters	Gap-acceptance parameters (Follow-up Headway, Critical Gap), entry lane-use model, circulating stream bunching represent driver behavior. Driver response times determined.	Gap-acceptance parameters (Follow-up Headway, Critical Gap), entry lane-use model, circulating stream bunching represent driver behavior.	No direct representation of any aspect of driver behavior. Capacity is sensitive to the circulating flow rate only.
	Follow-up Headway and Critical Gap depend on roundabout geometry.	Follow-up Headway, Critical Gap values are constant.	Not applicable.
	Follow-up Headway and Critical Gap values are reduced (more aggressive driver behavior) with increased circulating flow rates.	Follow-up Headway, Critical Gap values are constant.	Not applicable.
	Priority sharing and priority emphasis effects are included in the model.	Not applicable.	Not applicable.
Roundabout Geometry Parameters (list of geometry parameters affecting capacity)	Average entry lane width	Not used	Total entry width
	Number of entry lanes	Number of entry lanes	Not used
	Number of circulating lanes	Number of circulating lanes	Not used
	Inscribed diameter With increased inscribed diameter: capacity increases and then decreases for very large roundabouts.	Not used	Inscribed diameter With increased inscribed diameter: capacity increases with increasing inscribed diameter; capacity does not decrease for very large roundabouts.
	Entry radius	Not used	Entry radius
	Entry angle	Not used	Entry angle
	Approach short lane capacity and overflow into adjacent lane modeled using gap-acceptance cycles and back of queue modeling.	Short lanes modeled as an extension in SIDRA INTERSECTION software.	Approach flaring (Approach half width and Flare length). Interpolation for lane width between single and multilane approach values problematic.
	Number of exit lanes and exit short lanes (merge lanes) modeled through effect on upstream approach lane use (increased v/c ratio due to lane under-utilization).	Not applicable.	Not applicable.
Heavy Vehicles	Circulating flow rate is increased for heavy vehicles in the circulating stream. Follow-up Headway and Critical Gap values are increased for heavy vehicles in the entry lane.	Capacity is decreased for heavy vehicles directly.	*Not known to the author.*
Model Calibration	Intersection-level or approach-level calibration using Environment Factor. A general value of 1.2 used for US conditions. Movement-level calibration using Follow-up Headway and Critical Gap parameters.	Method described to calibrate the model parameters using known Follow-up Headway and Critical Gap values.	The y-intercept value of the linear regression capacity function can be adjusted. *(8,15)* Problematic since the capacity decreases with improved geometry (increased entry radius, decreased entry angle, etc) if the capacity at zero circulating flow is fixed.
	Sensitivity analysis facility is available for driver behavior and roundabout geometry parameters.	Offered as an extension in SIDRA INTERSECTION software.	*Not known to the author.*

It is seen from *Tables 1a and 1b* that, while the *SIDRA Standard* and *UK TRL* models differ significantly in being lane-based and approach-based models, they have many geometric parameters in common (although there are some geometric parameters which are not in the UK TRL model). Some of these parameters are discussed below.

Entry Radius and Entry Angle

New research has been carried out to extend the *SIDRA Standard* roundabout model to allow the effect of *entry radius* and *entry angle* parameters on roundabout capacity and implemented SIDRA INTERSECTION Version 5.1. These parameters have been used in the UK TRL model. The effect of these parameters on roundabout capacity is discussed below. The effect of the *inscribed diameter* parameter representing the overall size of the roundabout is also discussed.

In the *UK TRL* model, the entry radius and entry angle parameters are combined as a factor that applies to the y-intercept value as well as the slope of the capacity equation:

$$a = 1 - 0.00347\ (\phi_e - 30) - 0.978\ ((1 / r_e) - 0.05) \quad (4)$$

where r_e is the entry radius (m) and ϕ_e is the entry angle (degrees).

In the *SIDRA Standard* model, the entry radius and entry angle adjustment factors are calculated from:

$$f_r = 0.95 + 1 / r_e \quad (5a)$$

$$f_a = 0.94 + 0.00026 / \phi_e^{1.6} \quad (5b)$$

where r_e is the entry radius (m) and ϕ_e is the entry angle (degrees).

With customary units, *Equation (5a)* can be expressed as $f_r = 0.95 + 3.28 / r_e$ where r_e is in feet.

The entry radius and entry angle adjustment factors are used in the formula for the dominant lane follow-up headway at zero circulating flow. The effect of these factors is passed on to follow-up headway estimates for subdominant lanes and critical gap estimates for dominant and subdominant lanes through normal SIDRA equations.

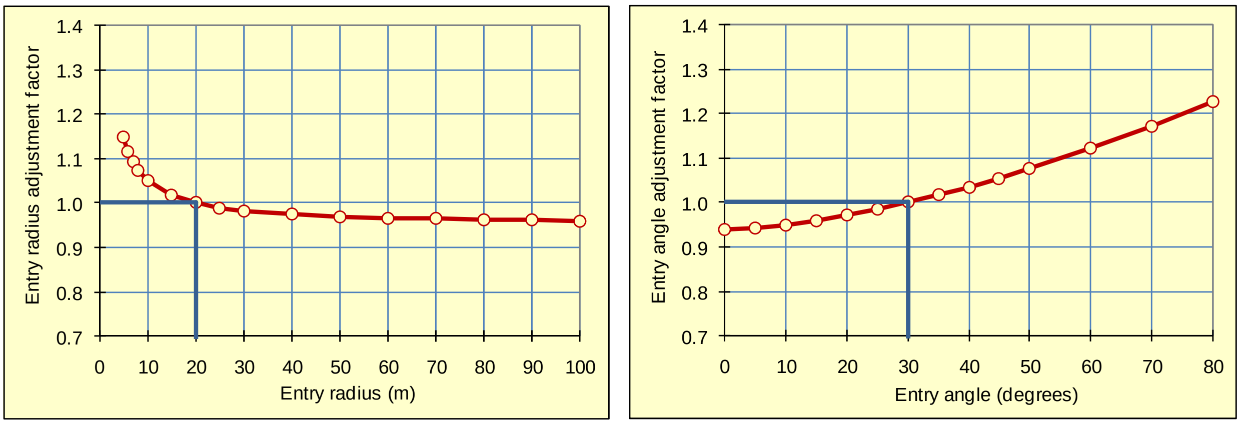

Figure 4 - Entry Radius and Entry Angle adjustment factors in *SIDRA Standard* model

Table 2

The entry radius and entry angle factors in *SIDRA Standard* and *UK TRL* models

r_e (m)	r_e (ft)	ϕ_e (degrees)	*UK TRL*	*SIDRA Standard*
5	16	70	1.40	1.35
10	33	60	1.18	1.18
20	66	45	1.05	1.05
30	98	35	1.00	1.00
40	131	**30**	0.98	0.98
60	197	15	0.92	0.93
80	262	5	0.89	0.91
100	328	0	0.87	0.90

As seen in *Figure 4*, the values of the adjustment factors are 1.0 at default values of the Entry Radius (20 m or 65 ft) and Entry Angle (30 degrees). Therefore, there will be no change to capacity estimates compared with Version 5.0 if the default values of these parameters are not changed. Larger values of Entry Radius and smaller values of Entry Angle give smaller critical gap and follow-up headway values and therefore result in larger capacity estimates. Smaller values of Entry Radius and larger values of Entry Angle have the opposite effect.

The values from *Equations (4) and (5)* for the *SIDRA Standard* and *UK TRL* models give very close values as seen in *Table 2*. For the SIDRA Standard model, the values shown in *Table 2* were calculated as the product of f_r and f_a.

Inscribed Diameter

The effect of the ***inscribed diameter*** parameter on capacity indicates some differences between the *SIDRA Standard* and *UK TRL* models. While both models indicate that capacity will increase with inscribed diameter, the *SIDRA Standard* model will estimate decreasing capacity (increasing v/c ratios) for very large roundabouts. An example is shown in *Figure 5* which is for case (ii) in the example given in this paper. In this example, the inscribed diameter is 132 ft (40 m), and 500% scale (applies to the central island diameter) in *Figure 5* means an inscribed diameter of 452 ft (138 m). *Figure 5* is the SIDRA INTERSECTION sensitivity output for the intersection as a whole. It shows the critical lane degree of saturation (highest for any lane) and the total effective capacity total demand divide by the critical degree of saturation). The Australian survey database included several very large roundabouts (max size was 220 m or 720 ft).

On the other hand, the *UK TRL* model does not estimate decreasing capacities for very large roundabouts. *Figure 6* shows the total approach capacity estimated by the *UK TRL* model for the WB (East) approach in Case (ii) in the example given in next section. It is seen that there is no decrease in capacity for very large diameter values. In the *UK TRL* model, the inscribed diameter parameter is used in the following factor that applies only to the slope of the capacity equation (not the y-intercept):

$$c = 1 + 0.5 / [1 + exp\,(0.1\,D_i - 6)] \qquad (6)$$

where D_i is the inscribed diameter (m).

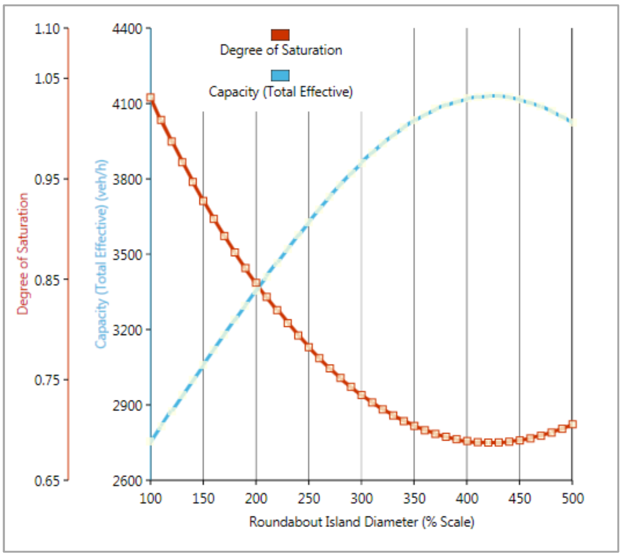

Figure 5 - Effective intersection capacity and critical degree of saturation as a function of the inscribed diameter estimated by the *SIDRA Standard* model

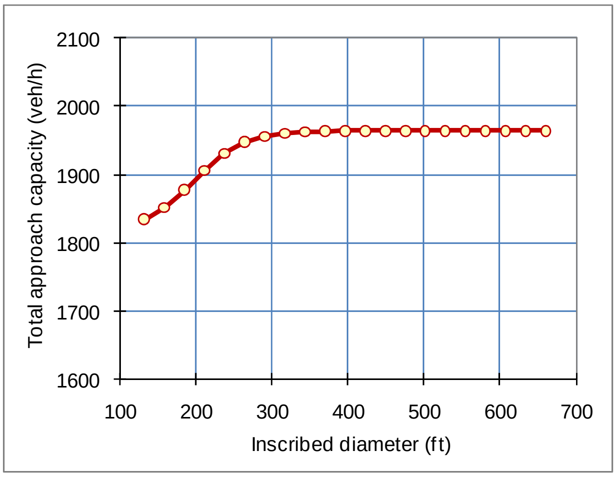

Figure 6 - Total approach capacity as a function of inscribed diameter estimated by the *UK TRL* model

Approach Flaring and Short Lanes

Another difference between the *SIDRA Standard* model and the *UK TRL* model in relation to the effect of geometric parameters on roundabout capacity is in the treatment of ***approach flaring***. The UK TRL model treats this through the use of total entry width, approach (upstream) half width and length of flare.

In the *SIDRA Standard* model, ***approach flaring*** effects are predicted through the use of **short lane** modeling (extra lane width which allows for an additional queue to form) and the **entry lane width** parameter (extra lane width at the yield / give-way line which is not sufficient for a separate queue to form). This ***short lane*** model applies to the HCM 2010 model in the SIDRA INTERSECTION software as an extension (short lane capacity and any excess flow into adjacent lanes are determined using equivalent gap-acceptance parameters from the HCM 2010 model). 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 which is based on geometric parameters only.

Short lanes at roundabouts can be very effective depending on flow conditions, but 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 movements 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 *(20)*.

A MULTILANE ROUNDABOUT EXAMPLE

The two-lane T-intersection roundabout example shown in *Figure 7* is used to compare estimates of capacity and degree of saturation (v/c ratio) from the *HCM 2010*, *SIDRA Standard*, and the *UK TRL* capacity models. This is based on an example presented by Chard *(19,20)* who demonstrated the lack of sensitivity of the *UK TRL* model to different approach lane use arrangements. The case is presented for driving on the right-hand side of the road as applicable to US driving conditions. The volumes are modified in order to demonstrate the importance of approach and circulating road lane use issues as well as unbalanced flow conditions.

A variety of options are feasible for approach and circulating lane arrangements for this roundabout, using various combinations of approach roads with exclusive or shared lanes and single-lane or two-lane circulating roads. The following two cases representing two different lane arrangements are considered:

Case (i): The roundabout has two-lane approach roads with ***shared lanes and two circulating lanes*** for all approach roads. This arrangement has balanced flows in approach lanes to make use of available lane capacities and offers entering vehicles better opportunity to accept gaps in multi-lane circulating streams.

Case (ii): This is an alternative arrangement with ***exclusive entry lanes and a single-lane circulating road*** for all approach roads. In this case, irrespective of specifying a single-lane or two-lane circulating road, all circulating streams would operate effectively as single-lane movements due to exclusive lane arrangements on approach roads (this reduces the capacity of the roundabout).

The geometry data are summarized in *Table 3* and the approach lane disciplines for the two cases are shown in *Figure 7*. The inscribed diameter is the same (132 ft / 40 m) for both cases. Geometric parameters other than number of lanes and lane disciplines are not used in the HCM 2010 model. Other geometric parameters are applicable to the *SIDRA Standard* and *UK TRL* models only (see *Tables 1a and 1b*). Although geometric parameters have been shown in both metric and US customary units, SIDRA INTERSECTION software was used with customary units for the analysis reported in this paper. The parameter values in metric and US customary units shown in *Table 3* are not necessarily precise converted values.

The circulating flow in front of each approach consists of traffic from one approach only at this roundabout. The entry and circulating flow rates indicate potential for unbalanced flow conditions.

For the *SIDRA Standard* model, Environment Factor of 1.2 is used. For the *HCM 2010* model, Origin-Destination factors or adjustment factors for Entry /Circulating Flow Ratio are not used, and the capacity constraint method applies in one case.

For the *UK TRL model*, the "capacity at zero circulating flow" (y intercept) is set equal to the HCM 2010 value of 2260 pcu/h (= 2 x 1130 for 2 entry lanes). The slope of the model is as predicted by the original model.

For the *HCM 2010* model, the capacity equation for "single-lane roundabouts" applies to all single-lane circulating road cases, including multilane approaches. For multilane approach lanes with multilane circulating roads, different equations apply.

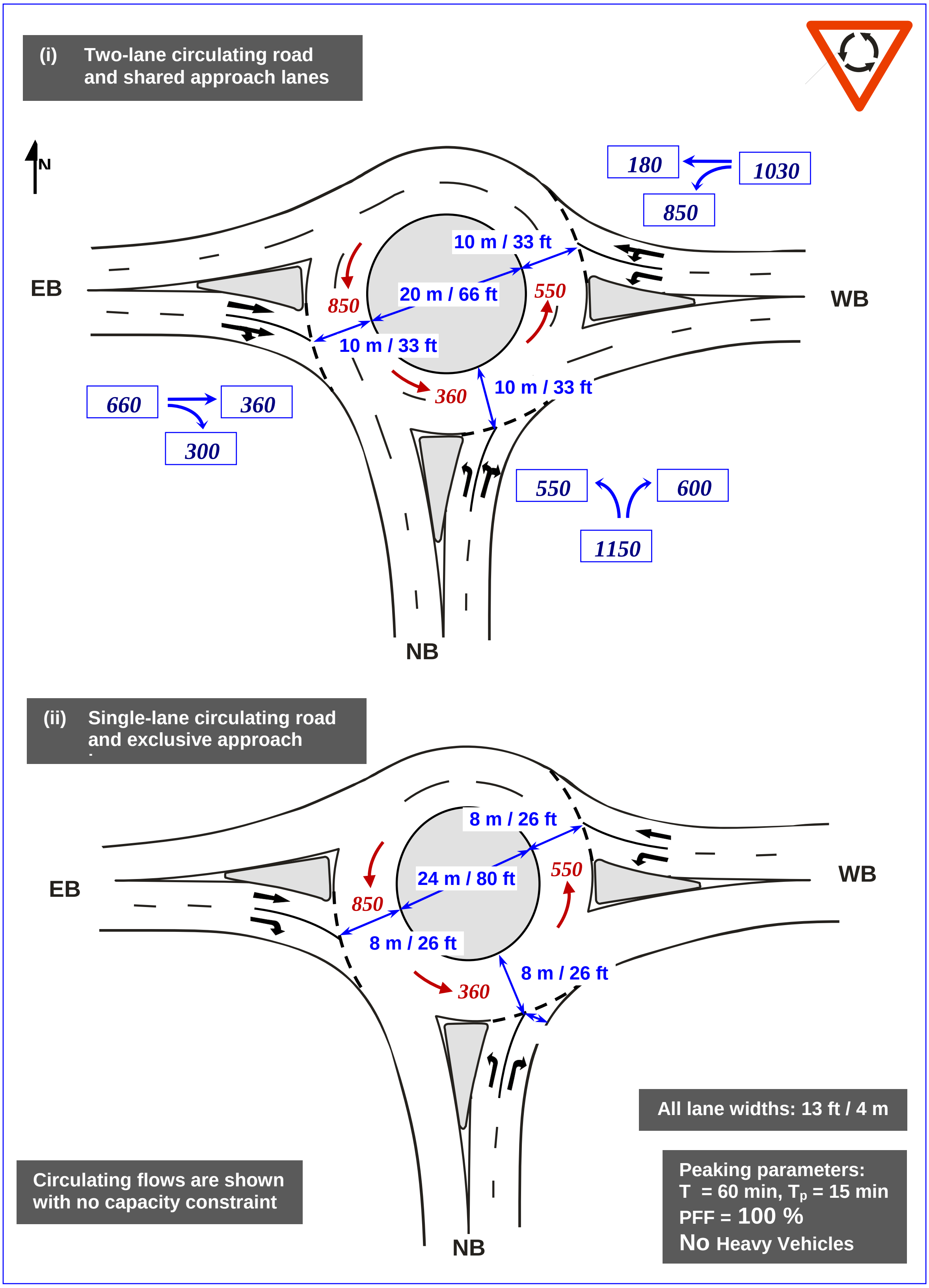

Figure 7 - Example 2: two cases of T-intersection roundabout with shared and exclusive lane arrangements

Table 3 - Geometry data for the T-intersection roundabout

		Parameters common to cases (i) and (ii)							
Approach ID	Approach Name	Average entry lane width	Total entry width	Number of entry lanes	Inscribed diameter	Approach half width	Flare length	Entry radius	Entry angle
W	Arm A	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (7 m)	70 ft (20 m)	65 ft (20 m)	30^{o}
S	Arm B	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (7 m)	70 ft (20 m)	65 ft (20 m)	30^{o}
E	Arm C	13 ft (4 m)	26 ft (8 m)	2	132 ft (40 m)	23 ft (7 m)	70 ft (20 m)	65 ft (20 m)	30^{o}

		Case (i): Two-lane circulating road and shared approach lanes			Case (ii): Single-lane circulating road and exclusive approach lanes		
		Number of circulating lanes	Central island diameter	Circulating road width	Number of circulating lanes	Central island diameter	Circulating road width
W	2	2	66 ft (20 m)	33 ft (10 m)	1	80 ft (24 m)	26 ft (8 m)
S	2	2	66 ft (20 m)	33 ft (10 m)	1	80 ft (24 m)	26 ft (8 m)
E	2	2	66 ft (20 m)	33 ft (10 m)	1	80 ft (24 m)	26 ft (8 m)

For the *HCM 2010* and *SIDRA Standard* capacity models, lane flows are determined according to the SIDRA INTERSECTION principle of equal degrees of saturation which assigns lower flow rates to lanes with lower capacity.

Analyses are carried out for 15-min peak period. The hourly flow rates calculated from 15-min peak volumes are shown in *Figure 7*. Peak Flow Factors are 1.0 due to the use of known peak flow rates.

Estimates of capacity and degree of saturation (v/c ratio) for critical lanes are given in *Table 4*. The critical lanes are identified by the lane-based *HCM 2010* and *SIDRA Standard* models directly as indicated in the table. For the approach-based *UK TRL* model, critical lanes cannot be identified. In this case critical lane flow rate and capacity values are calculated as half the total approach value. This means that the approach degree of saturation is used for all lanes for all cases in this model.

It is seen that the results from the *HCM 2010* and *SIDRA Standard* models are very close for Case (i) with a maximum difference of 6% in v/c ratios. The *UK TRL* model also gives lower v/c ratios, with a maximum difference of -24%. However, with low to medium degrees of saturation estimated by all models, the differences between delay and LOS estimates using the same methods would not be very high.

However, there are significant differences for Case (ii) where capacity estimates from the *HCM 2010* model for the South and East approaches are lower resulting in higher degrees of saturation, especially for the East approach. This is because the *HCM 2010* model estimates lower capacities for multilane approach lanes against a single circulating lane.

Table 4 - Capacity results for the T-intersection roundabout example with two cases of lane use arrangements

Approach	Total Approach Flow (veh/h)	Circulating Flow (pcu/h)	Critical Lane	Critical Lane Flow (veh/h)	Critical Lane Capacity (veh/h)	Degree of saturation (v/c ratio)
Case (i): Two-lane circulating road and shared approach lanes						
HCM 2010 Capacity Model						
NB (South)	1150	360	2 (R) ***[1]***	600 ***[1]***	878	0.68
WB (East)	1030	550	2 (LT)	522	769	0.68
EB (West)	660	**850**	2 (TR)	337	623	0.54
SIDRA Standard Capacity Model (Environment Factor = 1.2)						
NB (South)	1150	360	2 (R) ***[1]***	600 ***[1]***	887	0.68
WB (East)	1030	550	2 (LT)	515	719	0.72
EB (West)	660	**850**	2 (TR)	330	604	0.55
UK TRL Model (Capacity at Zero Circulating Flow = 1130)						
NB (South)	1150	360	Average	575	991	0.58
WB (East)	1030	550	Average	515	917	0.56
EB (West)	660	**850**	Average	330	801	0.41
Case (ii): Single-lane circulating road and exclusive approach lanes						
HCM 2010 Capacity Model						
NB (South)	1150	360	2 (R)	600	788	0.76
WB (East)	1030	550	1 (L)	**850**	**652**	**1.30**
EB (West)	660	**652** ***[2]***	1 (T)	360	589	0.61
SIDRA Standard Capacity Model (Environment Factor = 1.2)						
NB (South)	1150	360	2 (R)	600	987	0.61
WB (East)	1030	550	1 (L)	**850**	**824**	**1.03**
EB (West)	660	**824** ***[2]***	1 (T)	360	539	0.67
UK TRL Model (Capacity at Zero Circulating Flow = 1130)						
NB (South)	1150	360	Average	575	991	0.58
WB (East)	1030	550	Average	**515**	**917**	**0.56**
EB (West)	660	**850**	Average	330	801	0.41

[1] De facto Exclusive right-turn lane identified by the program (Lane 1 underutilised)

[2] In case (i), the circulating flow rate for the EB (West) approach includes capacity constraint effect due to oversaturation on East approach (x > 1.0). Circulating flows for Case (ii) are without any capacity constraint since all approach lanes are estimated to be undersaturated (x < 1.0).

Both the *SIDRA Standard* and *HCM 2010* models identify the problem of unbalanced lane flows due to user-specified exclusive lanes on all approaches. In particular, the problem of oversaturation for the critical lane on East approach is identified by both models. On the other hand, the *UK TRL* model fails to indicate the problem for this approach as originally demonstrated by Chard *(19,20)*.

Both the *SIDRA Standard* and *HCM 2010* models give capacity estimates which differ significantly between Cases (i) and (ii) whereas the UK TRL model estimates for the two cases are the same as it is an approach-based model.

Both the *SIDRA Standard* and *HCM 2010* models estimate oversaturated conditions for the WB (East) approach in the case of single-lane circulating road with exclusive lanes, but estimate satisfactory operating conditions in the case of two-lane circulating road with shared lanes. These models estimate more favorable gap-acceptance conditions in the case of two-lane circulating flows, and the approach lane use is more balanced with shared lanes. The *UK TRL* model estimates satisfactory conditions for both cases.

Using a lane-by-lane method, the *SIDRA Standard* and *HCM 2010* models identify critical lanes distinguishing between exclusive and shared lane cases and allowing for any unequal lane utilization, thus identifying oversaturation on the East approach in the case of single-lane circulating road with exclusive lanes. They identify the NB right-turn lane as a *defacto exclusive* lane in Case (i). On the other hand, the *UK TRL* model combines exclusive and shared lanes to obtain an average approach degree of saturation, and therefore cannot identify defacto exclusive lanes, any cases of unequal lane utilization and cannot distinguish between different lane use arrangements.

To demonstrate the importance of distinguishing between the capacity and performance estimates for Cases (i) and (ii), SIDRA INTERSECTION software estimates of delay, operating cost, fuel consumption and CO_2 emission using the *SIDRA Standard* model show that, considering annual values of one hour of traffic operation only, the difference between the two cases amount to approximately 5,500 person-hours of delay, US$70,000 in operating cost, 2,500 gal of fuel consumption and 24,000 kg of CO_2 emission per year.

The difference between the two cases using the *HCM 2010* model are much higher due to much higher congestion level estimated for the WB approach (approximately 22,000 person-hours of delay, US$250,000 in operating cost, 8,000 gal of fuel consumption and 77,000 kg of CO_2 emission per year).

CONCLUDING REMARKS

Three well-known analytical models of roundabout capacity, namely the *SIDRA Standard* model, *HCM 2010* model and the UK TRL model have been compared through discussion of their basic features and estimates of capacity and degree of saturation (v/c ratio) produced by these models for a multilane roundabout example. It is shown that these models have some common features as well as significant differences. The aim of the paper is to enhance understanding of the fundamental aspects of different roundabout capacity models available around the world.

Further comparison of these and other models using case studies is recommended in view of many other key parameters involved in real-life situations, e.g. the effect of short lanes, variations in various geometric and driver behavior parameters, effect of upstream signals, effect of pedestrians, and so on. Comparison of performance estimates from these analytical models and microsimulation models are also of great interest.

ACKNOWLEDGEMENTS

The author is the developer of the SIDRA INTERSECTION model, and comments presented in this paper regarding other models should be read with this in mind.

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