Akcelik & Associates Pty Ltd
PO Box 1075G, Greythorn, Vic 3104 AUSTRALIA
info@sidrasolutions.com

Management Systems Registered to ISO 9001
ABN 79 088 889 687

REPRINT

An Assessment of the Highway Capacity Manual 2010 Roundabout Capacity Model

RAHMI AKÇELIK

REFERENCE:

R. AKÇELIK (2011). An Assessment of the Highway Capacity Manual 2010 Roundabout Capacity Model. *Paper presented at the International Roundabout Conference, Transportation Research Board, Carmel, Indiana, USA, 18-20 May 2011. Minor revision: 23 April 2012*

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 Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further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.

© Akcelik and Associates Pty Ltd / www.sidrasolutions.com
PO Box 1075G, Greythorn Victoria 3104, Australia
Email: info@sidrasolutions.com

ABSTRACT

This paper presents an assessment of the roundabout capacity model given in the new Highway Capacity Manual 2010 (HCM 2010) with a focus in its use in the SIDRA INTERSECTION software. The model which is based on US research on roundabouts (NCHRP 572) can be viewed as a non-linear empirical (regression) model with a theoretical basis in gap-acceptance methodology. The general importance of some fundamental aspects of the model is discussed. Various shortcomings of the HCM 2010 roundabout capacity model listed in HCM 2010, Chapter 21, and some related model extensions provided by the SIDRA INTERSECTION software, one of the alternative tools referred to in HCM 2010, are discussed with a view to future development of the HCM roundabout capacity model. Using a multilane roundabout example given in HCM 2010, capacity and the resulting degree of saturation (v/c ratio), delay, level of service and queue length estimates from the *HCM 2010* model are compared with those from the *SIDRA Standard* capacity model for roundabouts (using an Environment Factor of 1.2 for US conditions). Discussions are presented in relation to the finding of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts and the issue of possible increases in roundabout capacities in the USA over time due to changes in driver behavior. A possible calibration of the HCM 2010 model for moderate capacity increases expected in the future is presented making use of a driver behavior model.

INTRODUCTION

The new 2010 edition of the Highway Capacity Manual, Chapter 21 presents a lane-based capacity model for single-lane and two-lane roundabouts *(1)*. The model is based on research on US roundabouts as described in NCHRP Report 572, Chapter 4 *(2-5)*, and it has been adopted in the new TRB - FHWA Roundabout Informational Guide (NCHRP Report 672) *(6)*.

The HCM 2010 roundabout capacity model is described and the general importance of some fundamental aspects of the model is discussed. Various shortcomings of the HCM 2010 roundabout capacity model listed in HCM 2010, Chapter 21, and some related model extensions provided by the SIDRA INTERSECTION software, one of the alternative tools referred to in HCM 2010, are discussed with a view to future development of the HCM roundabout capacity model.

The HCM 2010 roundabout capacity model has been fully integrated into the SIDRA INTERSECTION Version 5.1 with significant extensions, and is the default option for the US HCM (Customary) and US HCM (Metric) versions of the software *(7)*.

The *SIDRA Standard* capacity model option in SIDRA INTERSECTION is based on research on Australian roundabouts *(8-21)* thus reflecting Australian driver characteristics. When the early results of the NCHRP 3-65 research leading to NCHRP Report 572 were published *(3-5)*, indicating that capacities of roundabouts in the USA were significantly lower compared with Australian and UK roundabouts, the *SIDRA Standard* capacity model was calibrated for US applications to provide capacity estimates closer to those observed in the USA. For this purpose, the Environment Factor parameter of the model was set to 1.2 as the default for US HCM versions of SIDRA INTERSECTION while the value of this parameter for Australian conditions is 1.0.

This paper investigates differences between capacities estimated by the *HCM 2010* and *SIDRA Standard* models using a multilane roundabout example given in HCM 2010.

HCM 2010 also introduced delay and queue equations for roundabout analysis and recommended a level of service (LOS) method that uses the same delay thresholds as those used for sign-controlled intersections. The degree of saturation (v/c ratio), delay, level of service and queue length estimates using the *HCM 2010* and *SIDRA Standard* models are also compared for the HCM 2010 multilane roundabout example.

The paper discusses the issue of lower capacity of roundabouts in the USA compared with Australian and UK roundabouts, and possible increases in roundabout capacities in the USA over time due to changes in driver behavior. A possible calibration of the HCM 2010 model for moderate capacity increases expected in the future is presented making use of a driver behavior model.

HCM 2010 acknowledges the need to use alternative models in view of various shortcomings it lists about the HCM 2010 roundabout capacity model. SIDRA INTERSECTION is one of the alternative tools referred to in HCM 2010. Implementation of the HCM 2010 model in SIDRA INTERSECTION software provides some extensions to the HCM 2010 model. Some of these extensions and related issues are discussed in *Appendix A* with a view to future development of the HCM roundabout capacity model. Issues related to the delay and queue length models and the Level of Service method given in HCM 2010 are discussed in *Appendix B*.

HCM 2010 ROUNDABOUT CAPACITY MODEL

HCM 2010 describes an exponential model of capacity for single-lane and two-lane roundabouts *(1)*. HCM 2010 states that this is a "combination of simple, lane-based regression and gap-acceptance models". In other words, the model can be viewed both as an *empirical* (exponential regression) model and a *gap-acceptance* model.

In SIDRA INTERSECTION, the HCM 2010 roundabout capacity model for an *entry lane* is expressed as:

$$Q_g = f_{HVe}\, f_p\, f_A\, A\, e^{-(B / f_B)\, q_m} \qquad (1)$$

where parameters A and B are related to the follow-up headway and critical gap parameters:

$$A = 3600 / t_f \quad \text{or} \quad t_f = 3600 / A \qquad (2a)$$

$$B = t_o / 3600 = (t_c - 0.5\, t_f) / 3600 \quad \text{or} \quad t_c = 3600\, B + 0.5\, t_f \qquad (2b)$$

and f_{HVe} = heavy vehicle factor for entry lane capacity, f_p = pedestrian factor for the effect of pedestrians crossing in front of entry lanes, f_A = adjustment factor for parameter A, f_B = adjustment factor for parameter B, q_m = opposing (conflicting) flow rate in pcu/h (adjusted for heavy vehicles), t_f = follow-up headway (s), t_c = critical gap (s) and t_o = a parameter that relates critical gap and follow-up headway parameters (s).

The opposing (conflicting) flow rate, q_m in *Equation (1)* is normally the circulating flow rate in front of the subject lane but may include a percentage of exiting flow rate depending on user specifications. Parameters A and B, and the corresponding gap-acceptance parameters (t_f, t_c) are given in *Table 1*.

Table 1 HCM 2010 roundabout model parameters

	A	B	t_f	t_c	t_o	t_f / t_c
Single-lane circulating stream (n_c = 1)						
Single-lane entry (n_e = 1, n_c = 1)	**1130**	**0.00100**	3.19	5.19	3.60	0.615
Multi-lane entry (n_e > 1, n_c = 1): apply to all lanes	**1130**	**0.00100**	3.19	5.19	3.60	0.615
Multi-lane circulating stream (n_c > 1)						
Single-lane entry (n_e = 1, n_c > 1) *	**1130**	**0.00070**	3.19	4.11	2.52	0.776
Multi-lane entry (n_e > 1, n_c > 1)						
Dominant lane (Right lane for US driving)	**1130**	**0.00070**	3.19	4.11	2.52	0.776
Subdominant lane (Left lane for US driving)	**1130**	**0.00075**	3.19	4.29	2.70	0.744

n_e = number of entry lanes, n_c = number of circulating lanes.

For the *HCM 2010* model, the heavy vehicle factor for an entry lane, f_{HVe} in *Equation (1)* is determined from:

$$f_{HVe} = 1.0 / [1.0 + (e_{HV} - 1.0)\, p_{HVe}] \qquad \textit{subject to } e_{HV} > 1.0 \tag{3}$$

where e_{HV} is the passenger car equivalent of a heavy vehicle for gap-acceptance purposes (pcu / veh), and p_{HVe} is the proportion of heavy vehicles in the entry lane traffic stream (the default value of e_{HV} is 2.0).

The opposing (conflicting) flow rate in pcu/h is determined:

$$q_o = q'_o / f_{HVo} \tag{4}$$

where q_o = adjusted opposing flow rate in *pcu/h*, q'_o = opposing flow rate in *veh/h*, and f_{HVo} = heavy vehicle factor calculated from:

$$f_{HVo} = 1.0 / [1.0 + (e_{HV} - 1.0)\, p_{HVo}] \qquad \textit{subject to } e_{HV} > 1.0 \tag{5}$$

where p_{HVo} is the proportion of heavy vehicles in the opposing stream, and e_{HV} is as in *Equation (3)*.

The calibration factors f_A and f_B are similar to the Environment Factor in the *SIDRA Standard* model. Values of f_A and f_B greater than 1.0 will increase capacity and values less than 1.0 will decrease capacity. Using $f_A = f_B$ will mean that the ratios of Follow-op Headway to Critical Gap (t_f / t_c) are kept unchanged. The values of f_A and f_B can be determined from:

$$f_A = f_B = Q' / Q \tag{6}$$

where Q' / Q = ratio of the Measured Capacity to the Estimated Capacity.

For example, $f_A = f_B = 1.10$ for 10 per cent increase in capacity of single lane roundabouts (A = 1130 and B = 0.001 corresponding to t_f = 3.186 s and t_c = 5.193 s, hence t_f / t_c = 0.614), the following results are obtained: A' = f_A A = 1243, B' = B / f_B = 0.000909 corresponding to t_f = 3600 / A' = 2.896 s t_c = 3600 B' + 0.5 t_f = 3.272 + 1.448 = 4.720 s, and t_f / t_c = 2.896 / 4.720 = 0.614.

FUNDAMENTAL ASPECTS OF THE HCM 2010 MODEL

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 *(1-2)*. 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 *SIDRA Standard* 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 report 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 Standard* method about the importance of allowing for driver behavior in roundabout capacity models *(7)*, and is in sharp contrast with the UK TRL method *(24)*. 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 *(7, 21-23)*. 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 *(24-28)* 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 increasing levels of model coarseness.

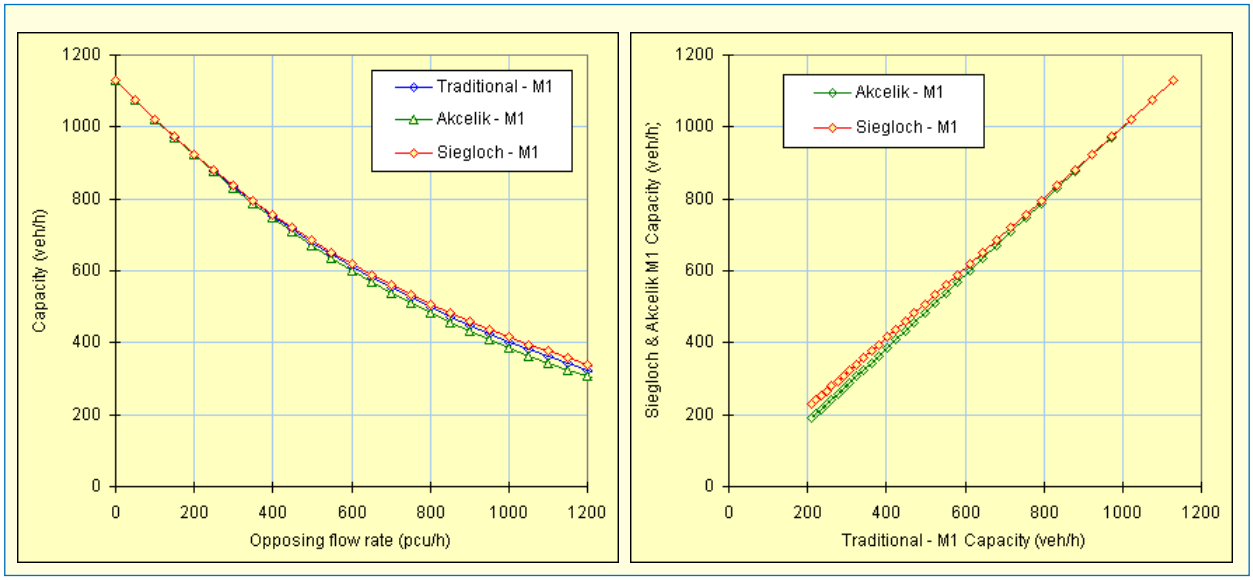

Figure 1 - Comparison of Traditional M1, Siegloch M1 and Akçelik M1 models (example using t_f = 3.19 s, t_c =5.19 s)

The HCM 2010 exponential regression model has the same form as the ***Siegloch*** M1 gap-acceptance model (an *M1 model* refers to the assumption of random arrivals of vehicles with no bunching) *(15)*. 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.

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 *(15)*.

The Traditional M1, Siegloch M1 and Akçelik M1 models (all assuming random arrival headways) give very close results *(15)*. This is shown in *Figure 1* for an example using the default gap-acceptance parameter values of t_f = 3.186 s (follow-up headway) and t_c = 5.193 s (critical gap) corresponding to the HCM 2010 single-lane roundabout model. It is seen that Akçelik M1 model gives slightly lower values for high circulating (opposing) flow rate. This is a desirable feature as the NCHRP Report 572 states that the exponential regression model (Siegloch M1) "*tends to overestimate capacities at higher circulating flows*". It would be interesting to assess the ***Akçelik M1*** model using the NCHRP 572 capacity data.

The NCHRP Report 572 also showed that the capacity model using exponential regression and the capacity model using the model parameters derived from average field values of the critical gap and follow-up headway parameters (t_f and t_c) are very close. Thus modeling capacity by a gap-acceptance method (using the critical gap and follow-up headway 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.

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

MULTILANE ROUNDABOUT EXAMPLE

Examples comparing the *HCM 2010* (using the NCHRP 572 method in earlier versions of SIDRA INTERSECTION) and *SIDRA Standard* roundabout capacity models for single-lane and multilane roundabout examples are given in an earlier paper *(21)*. Those examples showed that the capacities and degrees of saturation (v/c ratios) estimated by the two models were very close showing that the *SIDRA Standard* model with an Environment Factor of 1.2 approximated the HCM 2010 model closely. For the single-lane roundabout example, the capacities differed by about 3-4 % only. The multilane example showed that, as lane-based models, both the *HCM 2010* and *SIDRA Standard* were able to identify unbalanced lane flows and allow for unequal lane utilization by distinguishing between exclusive and shared lane cases. Both models gave capacity estimates which differed significantly from those given by the approach-based UK TRL model.

A multi-lane roundabout example shown in *Figure 2* is used to compare capacity estimates and the resulting degrees of saturation (v/c ratio), delay, LOS and queue length estimates from the *HCM 2010* and *SIDRA Standard* capacity models. This roundabout example which has a mixture of one and two-lane entries and circulating roads is *Example Problem 2* given in the Highway Capacity Manual 2010, Chapter 21. The entry flows represent a fairly balanced origin-destination flow pattern. There are no pedestrian effects.

Analyses are carried out for a 15-min peak period. For the *SIDRA Standard* capacity model, Environment Factor of 1.2 is used.

Three sets of geometric parameters are used (*Table 2*) in order to examine sensitivity to these parameters, namely *default values* (also shown in *Figure 2*), *less favorable values* (chosen to give *lower capacities* relative to default values) and *more favorable values* (chosen to give *higher capacities* relative to default values).

Although geometric parameters have been shown in both metric and US customary units, the latter system is used in the analysis reported in this paper. The parameter values in metric and US customary units are not precise converted values.

For the *HCM 2010* model, Origin-Destination factors or adjustment factors for Entry /Circulating Flow Ratio are not used. Geometric parameters other than number of lanes and lane disciplines are not relevant.

For both 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. However, in Example 1 a lane utilization factor has been specified for the *HCM 2010* model case in order to match lane flows determined in the HCM 2010.

The heavy vehicle adjustment method as given by *Equation (3)*, i.e. adjustment for all heavy vehicles has been used in all cases.

In this example, HCM 2010 method assigns 53% of total volume to Lane 2 (right lane) on Eastbound approach. To match the resulting lane flows, a lane utilization factor of 89% was specified for the same lane. This means that the v/c ratio of Lane 1 is 89 % of the v/c ratio of Lane 2. SIDRA method of lane flow calculation based on equal degrees of saturation assigns equal volumes to Lanes 1 and 2 using the *HCM 2010* model since the *HCM 2010* model estimates equal capacities for the two entry lanes in the case of single circulating lane (this applies to Eastbound and Westbound approaches).

On the other hand, *SIDRA Standard* model estimates higher capacity for Lane 2 and assigns 52% of total volume to Lane 2 on the basis of equal degrees of saturation. Lane utilization ratios to match the HCM 2010 lane flows were not used with the *SIDRA Standard* model for this example in order to represent the default solution method.

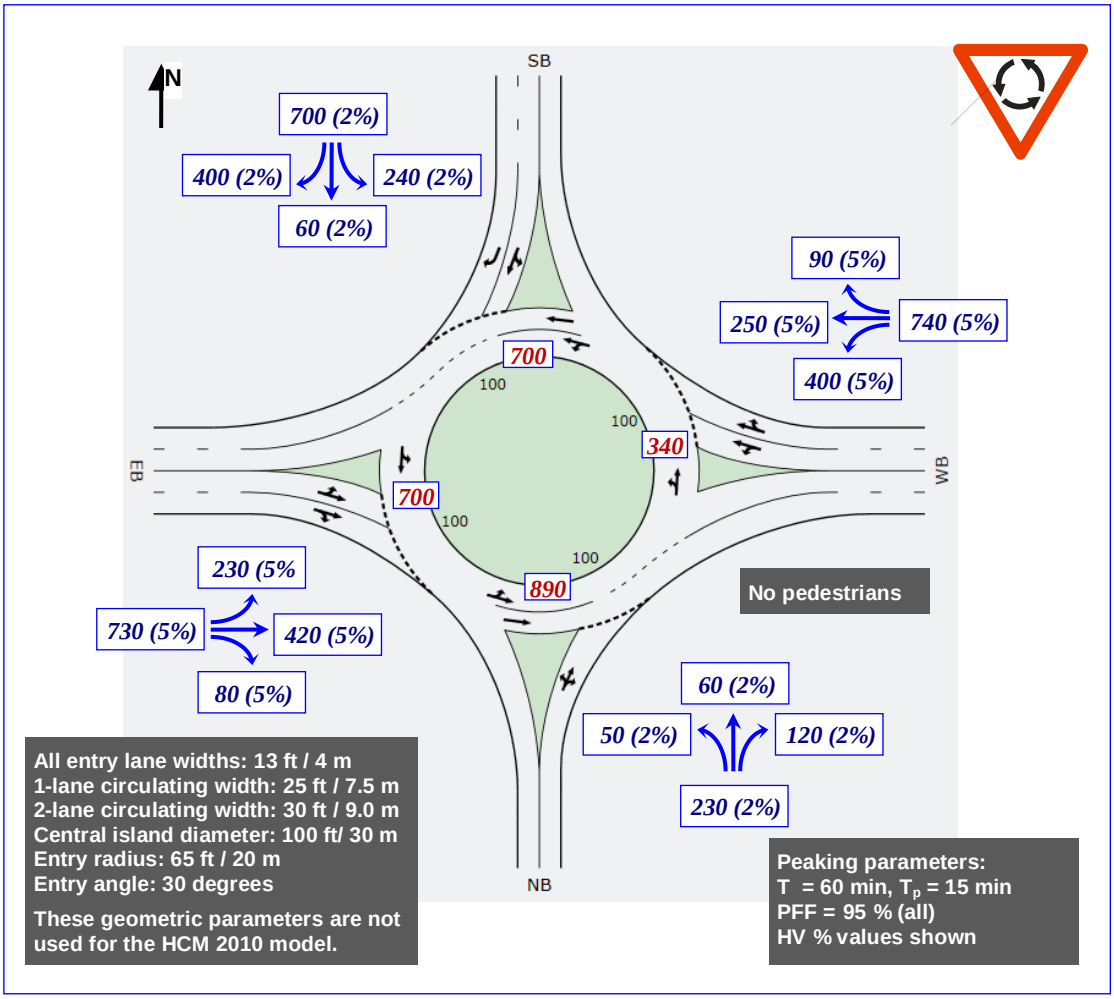

Figure 2 - Multilane four-way roundabout example (Example 2 in HCM 2010, Chapter 21)

Table 2 - Example 1 (4-way roundabout): Geometry parameters for *SIDRA Standard* capacity model (with Environment Factor = 1.2)

Entry lane width	Central island diameter	Circulating road width 1-lane	Inscribed diameter (1-lane circulating)	Circulating road width 2-lane	Inscribed diameter (2-lane circulating)	Entry radius	Entry angle
Default values							
13 ft (4.0 m)	100 ft (30 m)	25 ft (7.5 m)	150 ft (45 m)	30 ft (9 m)	160 ft (48 m)	65 ft (20 m)	30°
Less favorable values							
12.5 ft (3.8 m)	80 ft (25 m)	21 ft (6.5 m)	122 ft (38 m)	26 ft (8 m)	132 ft (41 m)	50 ft (15 m)	40°
More favorable values							
14 ft (4.3 m)	120 ft (36 m)	28 ft (8.5 m)	176 ft (53 m)	33 ft (10 m)	186 ft (56 m)	100 ft (30 m)	20°

The parameter values in metric and customary units are not precise converted values.
Values in customary units have been used in the analysis reported in this paper.

Table 3 - Capacity results for the example shown in *Figure 2* and data given in *Table 2*

Approach	Approach Flow (veh/h)	Circulating Flow (pcu/h)	Capacity Lane 1 (veh/h)	Capacity Lane 2 (veh/h)	Degree of saturation (v/c ratio)	Average delay (s/veh)	LOS	95%Back of Queue (ft)
Capacity model = *HCM 2010* (SIDRA INTERSECTION implementation) **Delay model = HCM 2010, Roundabout LOS method = "Same as Sign Control"**								
NB (South)	242	937	559	na	0.43	13.4	B	37
WB (East)	779	358	742	742	0.57	12.9	B	87
SB (North)	737	737	621	645	0.65	16.8	C	80
EB (West)	768	737	501	501	0.81	31.5	D	159
Capacity model = *SIDRA Standard* (Environment Factor = 1.2) **Delay model = SIDRA, Roundabout LOS method = "Same as Signalized Intersections"**								
Geometric parameters: Default values								
NB (South)	242	937	367	na	0.66	17.7	B	82
WB (East)	779	358	909	842	0.46	11.8	B	77
SB (North)	737	737	558	584	0.72	15.1	B	120
EB (West)	768	737	578	615	0.64	15.5	B	113
Geometric parameters: Less favorable values								
NB (South)	242	937	288	na	0.84	29.4	C	133
WB (East)	779	358	773	759	0.55	13.5	B	106
SB (North)	737	737	475	475	0.89	24.1	C	207
EB (West)	768	737	491	491	0.78	22.2	C	167
Geometric parameters: More favorable values								
NB (South)	242	937	474	na	0.51	12.6	B	54
WB (East)	779	358	1061	935	0.40	10.8	B	58
SB (North)	737	737	661	772	0.58	11.9	B	78
EB (West)	768	737	661	768	0.54	12.1	B	81

Degree of saturation (v/c ratio): critical lane value (highest for any lane).
Back of Queue based on SIDRA model (not given in HCM 2010): highest for any lane.
Different delay equations are used by the HCM 2010 and SIDRA Standard delay models.

In this example, both the *HCM 2010* and *SIDRA Standard* models identify the Westbound approach, Lane 1 as a defacto (exclusive) left-turn lane. Southbound Lane 2 is an exclusive right-turn lane specified as input. In both cases, the degrees of saturation (v/c ratios) of the two entry lanes are unequal, and the critical lane degree of saturation is higher than the value that would result from a balanced distribution of lane flows. This is an advantage of the lane-by-lane analysis method since an approach-based method like the UK TRL linear regression model inherently assumes a balanced distribution of lane flows.

The results from the *HCM 2010* and *SIDRA Standard* capacity models for this example are shown in *Table 3*. The results for three sets of geometric parameters for the *SIDRA Standard* model show sensitivities to these parameters, and establish a reasonable range of possible solutions.

The results summarized in *Table 3* indicate that, for multi-lane roundabouts, there may be significant differences in capacity estimates and the resulting degrees of saturation (v/c ratios), delays and queue lengths obtained using the *HCM 2010* and *SIDRA Standard* roundabout capacity models in SIDRA INTERSECTION. In particular, results obtained using the different sets of geometric parameters indicate that the *SIDRA Standard* model can give a wider range of variation from the *HCM 2010* model due to the lack of sensitivity to several geometric parameters in the *HCM 2010* model.

The approaches with worst degree of saturation, worst delay (and LOS) and worst queue length are seen to differ as well. In addition to the estimated v/c ratios, differences in the delay models used by the *HCM 2010* and *SIDRA Standard* models play a significant role in this.

DRIVER BEHAVIOR AND FUTURE CAPACITY INCREASES

The NCHRP Report 572 stated "*Currently, drivers in the United States appear to use roundabouts less efficiently than models suggest is the case in other countries around the world. In addition, geometry in the aggregate sense (number of lanes) has a clear effect on the capacity of a roundabout entry; however, 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.*" and "*Because driver behavior appears to be the largest variable affecting roundabout performance, calibration of the models to account for local driver behavior and changes in driver experience over time is highly recommended to produce accurate capacity estimates.*" *(2)*.

The question arises about whether capacity of US roundabouts will increase over time due to " *changes in driver experience over time*". Higher capacities from the models derived in Australia and UK might indicate potential increases in capacities of roundabouts which could be achieved in the USA with increased driver familiarity and increased driver aggressiveness due to higher demand and congestion levels at roundabouts in the future.

Rodegerdts *(4)* suggested that possible reasons for lower capacities at US roundabouts include driver unfamiliarity with roundabouts as a relatively new control device, larger vehicles, prevalence of stop control, especially use of all-way stop control and lack of use of two-way yield control, and lack of use of turn signals on exits causing driver hesitation during the yield process.

The factors for and against possible increase in roundabout capacities in the USA over time could be as follows.

For:

- In addition to the expected increase in efficiency in driver behavior due to increased familiarity, one could consider that increased congestion levels due to increased demand levels will also result in more aggressive driver behavior.
- The capacity is also affected by vehicle length (or queue space including gaps between vehicles in queue) and acceleration capability. If we consider that vehicle length will be reduced (effect of fuel cost and push for more efficient vehicles) and acceleration capabilities will improve in the future, then we would expect capacity increases associated with this as well.

Against:

- In terms of the all-way stop control and two-way yield control at minor intersections, the practice in Australia and UK is opposite to the US practice, i.e. all-way stop control is almost non-existent, and two-way yield signs are used commonly. If this difference is a significant factor affecting driver characteristics at roundabouts (more hesitant drivers who come to a complete stop before accepting gaps, resulting in lower capacities), it would be hard to speculate if this aspect of US driving culture and traffic control environment would not continue to affect roundabout capacities in the future. Note that lower gap-acceptance parameters are used in Australia for sign-controlled intersections as well, compared with those specified in the HCM based on US research on sign-controlled intersections.
- Recent roundabout research in Australia as part of our roundabout metering research *(19)* indicated that, on average, the follow-up headway and critical gap values in Australia did not change much since 1980s in spite of significant increases in demand and congestion levels at roundabouts.
- Preference for larger vehicles may not change over time, or changing vehicle population may mean somewhat reduced acceleration capabilities.

Calibrating the HCM 2010 Capacity Model for Expected Future Conditions

A method described by the author *(20)* for analyzing the relationship between capacity and driver behavior can be used to explore the idea of calibrating the HCM 2010 model for expected future conditions. The method uses the queue discharge headway (follow-up headway at roundabouts and sign-controlled intersections) as a key parameter that determines capacity, and expresses the driver response time during queue discharge as a function of the queue discharge headway, spacing between vehicles in the queue (jam spacing) and saturation (queue discharge) speed:

$$t_r = h_s - L_{hj} / v_s \qquad (6)$$

where h_s = the saturation (queue discharge) headway (seconds), t_r= driver response time during queue discharge (seconds), L_{hj} = queue space per vehicle (jam spacing) including the vehicle length and the gap distance between vehicles in the queue (metres or feet), and v_s = saturation speed (m/s or ft/s).

Equation (6) shows the importance of vehicle length and driver alertness which affect not only the driver response time but also the queue discharge speed and the gap distance left between vehicles in the entry lane queue (e.g. less gap under pressure of high traffic demand levels, more gap during bad weather conditions or uphill grade, and so on).

Application of *Equation (6)* to roundabouts was discussed previously *(20)*. This considered the Environment Factor value of 1.2 used in SIDRA INTERSECTION to calibrate the model to achieve lower capacities observed in the USA. For the Northbound approach in the example given in this paper, SIDRA INTERSECTION estimates a saturation speed of v_s = 20.8 mph (30.5 ft/s) and a jam spacing of L_{hj} = 25.4 ft including heavy vehicle effects for the *HCM 2010* capacity model. Using the follow-up headway of t_f = 3.19 s as the saturation headway (= h_s) for this model, a driver response time of t_r = 3.19 - 25.4 / 30.5 = 2.35 s is determined from *Equation (6)*.

Follow-up (queue discharge) headway and driver response times estimated by SIDRA INTERSECTION (based on *Equation 6*) for the example given in this paper are summarized in *Table 4*. The results are given for the *HCM 2010* capacity model and *SIDRA Standard* capacity model with *Environment Factor of* ***1.2*** to represent "current" US conditions (corresponding to the HCM 2010 model), including three cases of geometric parameters (corresponding to capacity results in *Table 3*).

Table 4 also gives estimates of follow-up (queue discharge) headway driver response times for the *SIDRA Standard* capacity model with *Environment Factor of* ***1.1*** to represent hypothetical "future" US conditions. The Environment Factor of 1.1 is selected considering the reasons for and against possible capacity increases in the future. This is used for the purpose of investigation as a value between the current value of 1.2 used to represent US conditions and the value of 1.0 used to represent Australian conditions.

Note that the *SIDRA Standard* model estimates decreasing follow-up headway, therefore more aggressive driver behavior with increasing circulating flow levels. This contributes to the variation of values estimated for the *SIDRA Standard* capacity model in addition to variations caused by changes in geometric parameters.

It is seen that changing the Environment Factor from 1.2 to 1.1 results in 0.2 to 0.3 second decrease in driver response times and follow-up headways all other factors being the same. On the basis of this result, consider reducing the follow-up headway used in the *HCM 2010* model from 3.19 s to 2.95 s. This is equivalent to increasing the current saturation flow rate of A = 1130 veh/ h to 1220 veh/h (from *Equation (2a)*, A = 3600 / t_f = 3600 / 2.95 = 1220).

The corresponding critical gap value can be calculated by applying the same reduction factor to keep the ratio of follow-up headway to critical gap (t_f / t_c) the same. For example, for single-lane circulating stream in *Table 1* (t_c = 5.19 s, B = 0.00100, t_f / t_c = 0.615), the reduced critical gap value can be calculated as t_c = 2.95 / 0.615 = 4.80 s. From *Equation (2b)*, B = (4.80 - 0.5 x 2.95) / 3600 = 0.000924 is found.

The values of A = 1220 and B = 0.000924 can then be used to calibrate the HCM 2010 model for future conditions. Alternatively, the general calibration parameters f_A and f_B used in *Equation (1)* can be used. For this example, they are f_A = 1220 / 1130 = 1.08 and f_B = 0.00100 / 0.000924 = 1.08 (equal values of factors are obtained due to the proportional adjustment of critical gap and follow-up headway values). It is necessary to carry out these calculations for all parameters in *Table 1*.

Table 4 - Follow-up (queue discharge) headway and driver response times estimated for the example shown in *Figure 2* (capacity results summarized in *Table 3*)

Approach Flow (veh/h)	Circulating Flow (pcu/h)	Capacity (veh/h)	Follow-up headway (s)	Driver response time (s)
Capacity model = ***HCM 2010*** using parameters given in *Table 1* ("current" US conditions)				
242 - 779	358 - 937	501 - 742	3.19	2.07 - 2.54
Capacity model = ***SIDRA Standard*** with Environment Factor = **1.2** ("current" US conditions)				
Geometric parameters: ***Default values***				
242 - 779	358 - 937	367 - 909	2.61 - 3.37	1.49 - 2.43
Geometric parameters: ***Less favorable values***				
NB (South)	358 - 937	288 -773	2.89 - 3.68	1.67 - 2.78
Geometric parameters: ***More favorable values***				
242 - 779	358 - 937	474 - 1061	2.38 - 3.12	1.33 - 2.34
Capacity model = ***HCM 2010*** with calibration factors $f_A = f_B$ = **1.1** ("future" US conditions)				
242 - 779	358 - 937	591 - 844	2.90	1.78 - 2.14
Capacity model = ***SIDRA Standard*** with Environment Factor = **1.1** ("future" US conditions)				
Geometric parameters: ***Default values***				
242 - 779	358 - 937	435 - 1024	2.39 - 3.09	1.27 - 2.26
Geometric parameters: ***Less favorable values***				
NB (South)	358 - 937	347 - 876	2.65 - 3.38	1.43 - 2.47
Geometric parameters: ***More favorable values***				
242 - 779	358 - 937	555 - 1190	2.18 - 2.86	1.13 - 2.08

Table 5 HCM 2010 roundabout model parameters to represent future conditions assuming calibration factors of $f_A = f_B = 1.1$.

	A	B	t_f	t_c	t_o	t_f / t_c
Single-lane circulating stream (n_c = 1)						
Single-lane entry (n_e = 1, n_c = 1)	**1240**	**0.00091**	2.90	4.72	3.27	0.614
Multi-lane entry (n_e > 1, n_c = 1): apply to all lanes	**1240**	**0.00091**	2.90	4.72	3.27	0.614
Multi-lane circulating stream (n_c > 1)						
Single-lane entry (n_e = 1, n_c > 1) *	**1240**	**0.00064**	2.90	3.74	2.29	0.775
Multi-lane entry (n_e > 1, n_c > 1)						
Dominant lane (Right lane for US driving)	**1240**	**0.00064**	2.90	3.74	2.29	0.773
Subdominant lane (Left lane for US driving)	**1240**	**0.00068**	2.90	3.90	2.45	0.744

n_e = number of entry lanes, n_c = number of circulating lanes.

The parameters for the *HCM 2010* capacity model to represent future conditions given in *Table 5* were determined calibration factors of $f_A = f_B = 1.10$. The corresponding capacity, follow-up headway and driver response time parameters for the example shown in *Figure 2* are also given in *Table 4*.

This analysis indicates that small reductions in driver response times due to the reasons considered above could result in significant capacity increases at US roundabouts over time. It is shown that the parameters of the HCM 2010 model can be calibrated accordingly and analysis of possible capacity increases over time can be carried out. The capacities obtained using the HCM 2010 model with parameters given in *Table 5* are more conservative than those to be obtained from the model with a Californian calibration study mentioned in HCM 2010, Chapter 33.

CONCLUDING REMARKS

This paper has emphasized the roundabout capacity model given in the 2010 Highway Capacity Manual as a non-linear empirical (exponential regression) model with a theoretical basis in gap-acceptance methodology. The model has been described and the general importance of some fundamental aspects of the model has been discussed. These include:

- The US research on roundabouts leading to the HCM 2010 capacity model *(1-2)* confirmed that, although important, roundabout geometry *alone* (as in the UK TRL model) is not sufficient for modeling capacity of roundabouts, and the capacity model must be related to driver behavior explicitly (as in the *SIDRA Standard* method).
- The HCM 2010 model offers the advantages of a *lane-based* method which models unbalanced lane flows resulting from user-specified and defacto exclusive lanes, thus avoiding underestimation of v/c ratios, delays and queue lengths on critical approach lanes. This is superior to both the *approach-based* UK TRL method for roundabout capacity and the *lane-group based* method used in the HCM for other intersections types.
- The HCM 2010 exponential regression model has the same form as the *Siegloch* M1 gap-acceptance model. As such, it belongs to the group of models that assume random vehicle arrival headways with no bunching *(15)* unlike the bunched exponential distribution of headways used in SIDRA INTERSECTION.

It is recommended that the comments presented in this paper and the extensions provided by the SIDRA INTERSECTION software as an alternative tool are taken into account in investigating various shortcomings of the HCM 2010 roundabout capacity model towards future development of the model. The related concerns include the following:

- It should be clarified if the HCM intersection delay models include *geometric delay*. This is of particular interest for roundabouts.
- It is desirable to use the *back of queue* formulation in HCM models for roundabouts and sign-controlled intersections including estimation of percentile queues other than 95th percentile queue. Use of the same queue definition would make HCM consistent for signalized and unsignalized intersections.
- The *Level of Service* (LOS) thresholds recommended by HCM 2010 for roundabouts, which are the same as those for *stop sign-controlled* intersections, create a bias against roundabouts when compared with signalized intersection treatments. This is of particular concern due to the low capacity and high delay estimates given by the HCM 2010 roundabout model. Although this issue was discussed during the development of HCM 2010, *alternative LOS thresholds for roundabouts* including the *SIDRA Roundabout LOS* should be given further consideration.

  The fact that roundabouts are significantly easier to negotiate being subject to *yield (give-way) sign* control with only one conflicting (opposing) stream compared with *two-way stop sign* control with many conflicting streams should be reflected in different LOS thresholds for these two very different types of control. Slower opposing stream speeds, lower follow-up headway

and critical gap values and higher capacities for roundabouts indicate that roundabouts are easier to negotiate than minor roads at intersections controlled by two-way stop signs.

The multilane roundabout example analyzed in this paper shows that there may be significant differences in capacity and performance estimates obtained using the *HCM 2010* and *SIDRA Standard* roundabout capacity models, especially considering the lack of sensitivity to a number of roundabout geometry parameters in the HCM 2010 model. SIDRA INTERSECTION users in the USA have been using the *SIDRA Standard* model for a long time. It will now be a difficult decision to continue using this model or choose the HCM 2010 model option. The latter is used as the default option in SIDRA INTERSECTION Version 5.1.

The calibration of the HCM 2010 model for moderate capacity increases expected in the future described in this paper may be useful towards understanding the relationship of the model parameters to driver behavior in more explicit terms.

A paper presenting further comparison of the *SIDRA Standard* and *HCM 2010* models as well as the UK TRL model is presented in another recent paper by the author.

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.

REFERENCES

1. TRB. *Highway Capacity Manual*. Transportation Research Board, National Research Council, Washington, DC, USA, 2010. ("*HCM 2010*")
2. TRB. *Roundabouts in the United States*. NCHRP Report 572. Transportation Research Board, National Research Council, Washington, DC, USA, 2007.
3. RODEGERDTS, L. State-of-the-Art in U.S. Roundabout Practice. Paper presented at the ITE 2005 Annual Meeting, Melbourne, Australia, 2005.
4. RODEGERDTS, L. Updated Roundabout analysis procedures for the next Highway Capacity Manual. Presentation at the *National Roundabout Conference*, Transportation Research Board, Kansas City, MO, USA, 2008.
5. KYTE, M., et al. NCHRP 3-65: Data Collection and Extraction. Paper presented at the *TRB National Roundabout Conference*, Vail, Colorado, USA, 2005.
6. TRB. *Roundabouts: An Informational Guide*. NCHRP Report 672. Transportation Research Board, National Research Council, Washington, DC, USA, in cooperation with US Department of Transportation, Federal Highway Administration, 2010.
7. AKCELIK and ASSOCIATES. *SIDRA INTERSECTION User Guide (for Version 5.1)*. Akcelik and Associates Pty Ltd, Melbourne, Australia, 2011.
8. AKÇELIK, R., CHUNG, E. and BESLEY, M. Performance of Roundabouts Under Heavy Demand Conditions. *Road and Transport Research* 5 (2), 1996, pp 36-50.
9. O'BRIEN, A., AKÇELIK, R., WILLIAMSON, D. and PANTAS, T. (1997). Three-laning a two-lane roundabout - the outcomes. *ITE 67th Annual Meeting*. Compendium of Technical Papers (CD).
10. AKÇELIK, R., CHUNG, E. and BESLEY, M. Analysis of roundabout performance by modelling approach flow interactions. *Proceedings of the Third International Symposium on Intersections Without Traffic Signals*, Portland, Oregon, USA, 1997, pp 15-25.

11. AKÇELIK, R., CHUNG, E. and BESLEY, M. Roundabouts: Capacity and Performance Analysis. Research Report ARR No. 321. ARRB Transport Research Ltd, Vermont South, Australia, 1999 (2nd Edn).

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

13. AKÇELIK, R. Roundabouts with Unbalanced Flow Patterns. Paper presented at the *ITE 2004 Annual Meeting and Exhibit*, Lake Buena Vista, Florida, USA, 2004.

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

15. AKÇELIK, R. A Review of Gap-Acceptance Capacity Models. Paper presented at the *29th Conference of Australian Institutes of Transport Research (CAITR)*, University of South Australia, Adelaide, Australia, 2007.

16. AKÇELIK, R. Roundabouts in Australia. Paper presented at the *National Roundabout Conferenc*e, Transportation Research Board, Kansas City, MO, USA, 2008.

17. AKÇELIK, R. Capacity and Performance Analysis of Roundabout Metering Signals. Paper presented at the *TRB National Roundabout Conference*, Vail, Colorado, USA, 2005.

18. AKÇELIK, R. Operating cost, fuel consumption and pollutant emission savings at a roundabout with metering signals. *ARRB 22nd Conference*, Canberra, 2006.

19. AKÇELIK, R. An investigation of the performance of roundabouts with metering signals. Paper presented at the *National Roundabout Conference*, Transportation Research Board, Kansas City, MO, USA, 2008

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

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

22. AKÇELIK, R. SIDRA-2 does it lane by lane. *Proc. 12th ARRB Conf.* 12 (4), pp 137-149, 1984.

23. AKÇELIK, R. 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), 1997, pp 388-399.

24. KIMBER, R.M. (1980). *The Traffic Capacity of Roundabouts*. TRRL Laboratory Report 942. Transport and Road Research Laboratory, Crowthorne, Berkshire, UK.

25. HOLLIS, E.M., SEMMENS, M.C. and DENNISS, S.L. (1980). *ARCADY: A Computer Program to Model Capacities, Queues and Delays at Roundabouts*. TRRL Laboratory Report 940. Transport and Road Research Laboratory, Crowthorne, Berkshire, UK.

26. KIMBER, R.M. (1989). Gap-acceptance and empiricism in capacity prediction. *Transportation Science* 23 (2), pp 100-111.

27. BROWN, M. (1995). *The Design of Roundabouts.* Transport Research Laboratory State-of-the-Art-Review. HMSO, London, UK.

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

29. AKÇELIK, R. 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, 2011.

APPENDIX A
MODEL EXTENSIONS - SIDRA INTERSECTION AS AN ALTERNATIVE TOOL

HCM 2010 acknowledges the need to use alternative models in view of various shortcomings it lists about the HCM 2010 roundabout capacity model. SIDRA INTERSECTION is one of the alternative tools referred to in HCM 2010. Implementation of the HCM 2010 model in SIDRA INTERSECTION software provides some extensions to the HCM 2010 model. These extensions are listed in the SIDRA INTERSECTION User Guide, and some of them are discussed below. Other issues related to the implementation of the HCM 2010 model in SIDRA INTERSECTION are also discussed in this section. These comments are provided with future development of the HCM roundabout capacity model in mind.

HCM 2010, Chapter 21 makes the following statement about the strengths of the HCM procedure: "*The procedures in this chapter were based on extensive research supported by a significant quantity of field data. They have evolved over several years and represent a body of expert consensus. They produce unique deterministic results for a given set of inputs, and the capacity of each approach is an explicit part of the results. Alternative tools based on deterministic intersection models also produce a unique set of results, including capacities, for a given set of inputs, while those based on simulation may produce different results based on different random number sequences. Unique results from an analysis tool are important for some purposes such as development impact review.*"

SIDRA INTERSECTION shares this basic premise with HCM 2010 as a "*deterministic intersection model*" using the HCM terminology. However, it should be noted that such mathematical models make allowance for stochastic nature of traffic behavior as evident from the randomness effects in delay and queue length equations, percentile queue values, effect of random arrival headways and random size and occurrence of bunches in traffic on gap-acceptance capacities, and so on.

The HCM 2010, Chapter 21 lists various "limitations of the HCM procedures that might be addressed by alternative tools". These limitations as addressed by SIDRA INTERSECTION through extensions to the *HCM 2010* model option or as part of the *SIDRA Standard* model option are discussed below.

Other issues related to the delay and queue models and the level of service method described in HCM 2010 model are discussed in some detail in the next section.

Upstream Signals

Effect of upstream signals on roundabout capacity is modeled using the *extra bunching* parameter. This is available for the *HCM 2010* option as well.

Theoretically, the Extra Bunching parameter does not affect gap-acceptance capacity in the case of random arrival distributions as it applies to the HCM 2010 roundabout capacity model. However, when the HCM 2010 capacity option is used and an extra bunching value has been specified for the effect of upstream signals, SIDRA INTERSECTION will apply an ***Extra Bunching Adjustment Factor*** to capacity. The Extra Bunching Adjustment Factor is determined from capacities obtained with and without extra bunching using the bunched exponential model used in the SIDRA Standard model.

Priority Reversal and Priority Emphasis

Priority reversal (priority sharing) between entering and circulating vehicles under high flow rates is related to low critical gap values at high circulating flow rates which may result in the condition $\mathbf{t_f + \Delta > t_c}$, where t_f = follow-up headway, t_c = critical gap (headway) and Δ = intra-bunch headway. Using the *SIDRA Standard* model, which uses a bunched exponential distribution of headways, this condition is identified and indicated in output. Under most conditions (except low circulating flow rates), gap-acceptance parameters estimated by the *SIDRA Standard* model imply priority sharing. The *Origin-Destination (O-D) Factor* in the *SIDRA Standard* model makes adjustment for the limited-priority gap-acceptance process although the process can be one of *priority emphasis* (opposite of priority reversal) in the case of unbalanced flow patterns *(13)*.

The priority reversal condition cannot be identified by the HCM 2010 model which assumes a random distribution of circulating stream headways (Siegloch M1 model) as discussed above. This model assumes zero intra-bunch value ($\Delta = 0$), and since $t_f < t_c$ is used for all conditions as seen in *Table 1*, priority reversal cannot be identified by the model. However, close values of the follow-up headway and critical gap values in *Table 1* indicate possibility of priority reversal in reality. Through the O-D Factor option, the priority reversal and priority emphasis can be allowed for to some extent with the HCM 2010 model in SIDRA INTERSECTION.

Capacity Constraint

It is necessary to apply the ***capacity constraint*** method when one or more lanes are oversaturated (v/c ratio above 1). This method limits the amount of traffic that can enter the roundabout circulating road from each oversaturated lane to its capacity value. This affects the circulating and exiting flow rates of downstream approaches, thus requiring iterative calculations. This essential element of roundabout modeling applies to the HCM 2010 model.

Unbalanced Flow Conditions

The effect of unbalanced conditions at roundabouts has been discussed by the author in previous publications *(12-14, 17-19)*. Unbalanced conditions cause loss of capacity at high demand flow conditions.

The ***Origin-Destination*** factor and adjustment factor for ***Entry /Circulating Flow Ratio*** for unbalanced flow conditions, which are important aspects of the *SIDRA Standard* roundabout model, can also be used for the *HCM 2010* model in the software (optional). These are useful in dealing with specific conditions rather than relying on a regression method for general average conditions. For example, it is recognized that drivers can be more aggressive when the entry flow rate is very high. Iterative calculations are needed to apply the ***Origin-Destination*** factor since this factor depends on the demand flow pattern as well as the amount of queuing on approach lanes.

Roundabout Metering Signals

Roundabout metering signals can be 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 (unbalanced) flows *(17-19)*. The use of metering signals is a cost-effective measure to avoid the need for a fully-signalized intersection treatment. The SIDRA INTERSECTION method for analysis of roundabout metering signals is available using the capacities from the *HCM 2010* model.

More Than Two Entry and Circulating Lanes

Roundabouts with more than 2 lanes and up to 8 legs can be analysed with any configuration of number of approach and circulating lanes, lane types and lane disciplines using the *HCM 2010* model or *SIDRA Standard* capacity model. These include single and multiple ***shared*** and ***exclusive slip lanes*** (*yielding bypass lanes*) controlled by yield or stop signs and ***continuous bypass lanes***.

The *SIDRA Standard* capacity model for roundabouts is sensitive to many parameters related to roundabout geometry, namely roundabout diameter, entry radius, entry angle, entry lane width, circulating lane width, number of entry lanes and circulating lanes, and other geometric parameters. However, the *HCM 2010* model is only sensitive to the number of entry and circulating lanes as seen through the parameter values in *Table 1*.

Flared Entries or Short Lanes

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 *(23)*. 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 which is based on geometric parameters only as used in ARCADY and RODEL software packages *(24)*.

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.

High Pedestrian Levels

The *HCM 2010* and *SIDRA Standard* models use the same method described in HCM 2010 for the effect of pedestrians on roundabout entry capacity. Exit lane capacities as a function of pedestrian flows are also determined for all roundabout legs using a gap-acceptance method. More detailed analysis of unsignalized and signalized pedestrian crossing on roundabout approaches can be carried out using facilities provided in SIDRA INTERSECTION. These models are generally available.

Closely Spaced Intersections

For analysis of closely-spaced multiple roundabouts, or pedestrian crossings near roundabouts, SIDRA INTERSECTION provides a *Capacity Adjustment* parameter which can be used to specify the amount of capacity reduction for upstream intersection lanes using the *probability of blockage* estimated for downstream intersection lanes where queue storage spaces are limited. This method applies to the HCM 2010 model.

Model Calibration

Model calibration is important for the applicability of the HCM 2010 model to different local conditions, and for accommodating changes in driver characteristics over time. HCM 2010 recommends calibration of the model by specifying values of parameters A and B in *Equations (1), (2a) and (2b)* using known follow-up headway and critical gap values. In other words, parameter values shown in *Table 1* can be changed on an approach basis with different parameters for single-lane and multi-lane cases.

Additionally, adjustment factors f_A and f_B can be used to carry out calibration of all parameters, e.g. considering conditions in the future. It is also possible to calibrate the model on a movement basis by specifying the follow-up headway and critical gap values for individual movements, including bypass (slip) lane movements subject to yield condition (slip lane movements).

Lane Flow Calculations

SIDRA INTERSECTION determines lane flows according to the e*qual degree of saturation* principle subject to user-specified and program-determined lane under-utilisation factors including downstream short lane effects. Furthermore, de facto exclusive lane cases are identified and taken into account appropriately during iterative lane flow calculations. The method applies to the HCM 2010 model including roundabouts with more than 2 lanes.

This method allocates lower volumes for lanes with lower capacities (subdominant lanes). The procedure described in HCM 2010 uses lane volume factors to allocate higher volumes to dominant lanes. Determining lane flows without considering lane capacities may end up allocating unduly high volumes into low-capacity lanes, resulting in high degree of saturation (v/c ratio) and high delay, and therefore unreasonable lane flow distributions (i.e. implying that drivers choose lanes with higher delay). This may

also manifest itself through inconsistent "critical lane" definition where the critical lane is defines as the lane with highest degree of saturation.

Heavy Vehicle Effects

For the *HCM 2010* model (*Equation 1*), heavy vehicle effects are taken into account by determining *heavy vehicle factors* for adjusting the opposing flow rates and the capacity estimate for heavy vehicles in the entry and circulating streams (*Equations 3 to 5*). The *SIDRA Standard* model uses the same method for opposing streams but adjusts the follow-up headway and critical gap values for heavy vehicle effects rather than adjusting the capacity estimate.

It is important that appropriate *heavy vehicle factors* are calculated for ***each lane*** rather than the whole approach since different heavy vehicle percentages for individual turning movements from an approach result in different heavy vehicle percentages per lane according to lane flow allocations. Ability for the analyst to specify the ***heavy vehicle equivalent*** (default value of 2) as input per movement is useful for model calibration in specific situations where there are large commercial vehicles in particular turning movements.

Performance Calculations

Back of queue and stop rate estimates, as well as fuel consumption, emission (including CO2) and operating cost estimates based on the HCM 2010 capacity model are important model extensions offered by SIDRA INTERSECTION. Roundabout negotiation speeds and distances are estimated and geometric delays are calculated as a function of approach, exit and negotiation speeds and distances, thus allowing for speed variations of vehicles negotiating roundabouts. Geometric delays are added to delay estimates allowing for roundabout negotiation speeds and distances. More detailed discussion on issues related to delay, queue length and level of service is given in the next section.

Potential Model Differences

Due to many model extensions available in SIDRA INTERSECTION, it is possible to obtain different capacity and performance results using the *HCM 2010* model option compared with the basic HCM 2010 procedure applied with no extensions.

Some procedures are implemented in the software for automatic update of some key parameters and options when the user changes the roundabout capacity model between the *HCM 2010* and *SIDRA Standard* options.

APPENDIX B
DELAY, QUEUE LENGTH, LEVEL OF SERVICE

Delay

The delay model given in HCM 2010, Chapter 10 is used when the *HCM Delay Formula* option (default when the US HCM versions of SIDRA INTERSECTION) is used. The HCM delay formula gives different results for a given capacity compared with the SIDRA Standard queue formula which is a little more detailed although the model structures are similar. Various definitions of delay need to be clarified when comparing different delay models. *Figures 3 and 4* are presented for this purpose.

SIDRA INTERSECTION defines the *control delay* as total time loss experienced in negotiating an intersection. This includes all acceleration and deceleration delays between the instant deceleration from approach cruise speed starts (point B in *Figures 3 and 4*) and the instant when the exit cruise speed is reached after negotiating the intersection (point G in *Figures 3 and 4*). Control delay includes *geometric delay* defined as the delay experienced by a vehicle negotiating the intersection in the absence of any other vehicles (without any queuing delays).

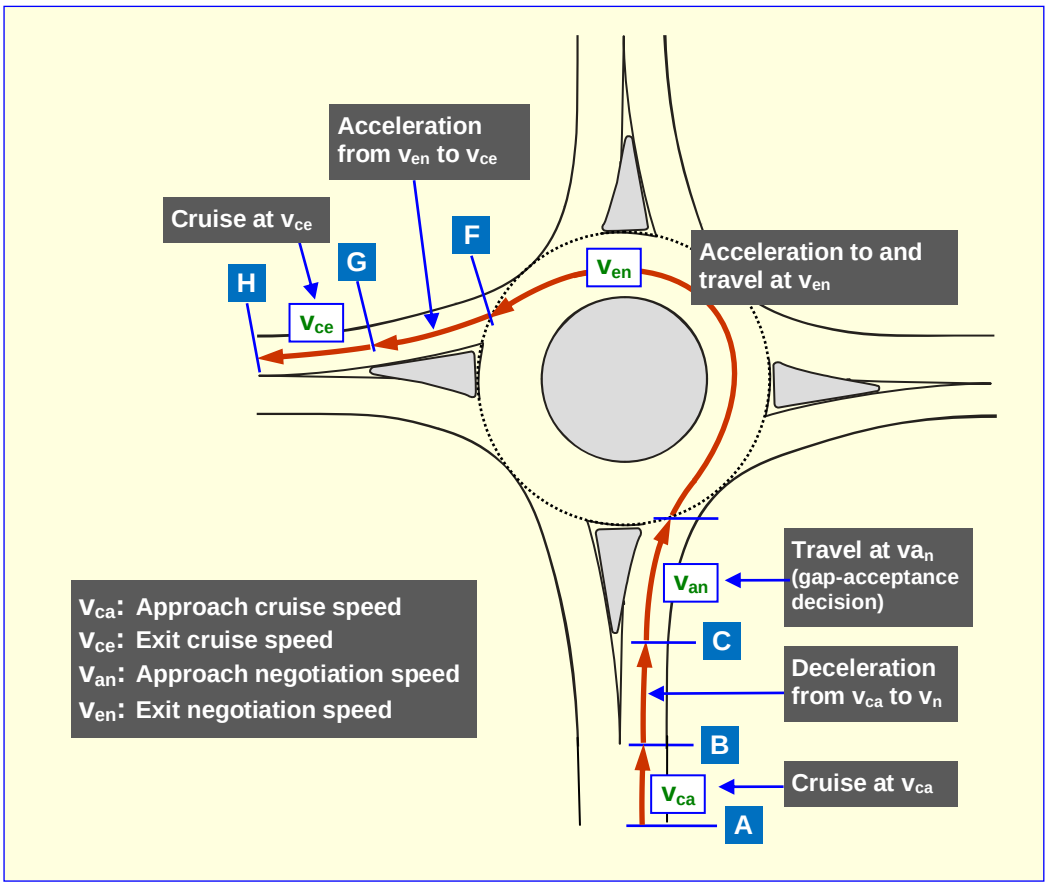

Figure 3 - Geometric delay parameters shown for an unqueued vehicle

Modeling of *geometric delay* at roundabouts is of particular importance. All vehicles slow down to a safe negotiation speed at roundabouts, and therefore experience a geometric delay. Geometric delay is determined as a function of approach and exit cruise speeds as well as the roundabout negotiation speeds, which depend on the geometric characteristics of the roundabout (negotiation radius and distance, and the associated speeds) as well the acceleration and deceleration characteristics of vehicles (*Figure 3*).

HCM 2010 qualifies its delay estimates as *control delay* although it is not clear if the HCM 2010 roundabout delay formula includes *geometric delay*. HCM 2010 delay formula includes an acceleration-deceleration term related to the proportion of vehicles queued [5 *min*(x,1.0)] where x is the v/c ratio used in lieu of proportion queued, and 5 s is the value when all vehicles are queued, x = 1.0]. This could be associated with stopping from the approach negotiation speed (movement C-D-E-F in *Figure 4*), and therefore considered to be part of the *stop-line delay*. In this case, the HCM roundabout delay formula does not include *geometric delay* (see *Figure 4*).

HCM 2010, Chapter 4, states that "*Delay is an important performance measure for interrupted-flow system elements. There are several types of delay, but control delay—the delay incurred due to the presence of a traffic control device—is the principal service measure in the HCM for evaluating LOS at signalized and unsignalized intersections. Control delay includes delay associated with vehicles slowing in advance of an intersection, the time spent stopped on intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speed.* "

HCM 2010, Chapters 19 and 20 for sign-controlled intersections give a formula for "average control delay" which includes a constant 5 s term which is explained as "The constant 5 s/veh is included to

account for the deceleration of vehicles from free-flow speed to the speed of vehicles in queue and the acceleration of vehicles from the stop line to free-flow speed.".

The explanations given in HCM Chapters 19 and 20 are in line with the definition of control delay in Chapter 4, and in line with the SIDRA Standard method since the control delay is defined essentially as a time loss relative to a *reference travel time* or travel at the *free-flow speed* or *desired speed* (which is represented by *approach and exit cruise speeds* in SIDRA INTERSECTION).

Thus, the meaning given to the extra 5 s delay in HCM 2010, Chapters 19 and 20 makes it *geometric delay* in SIDRA INTERSECTION terms. However, the acceleration and deceleration models used in SIDRA INTERSECTION indicate that 5 s geometric delay corresponds to a desired / free flow / cruise speed of around 25 km/h (acceleration-deceleration delay calculated for a 25 - 0 - 25 km/h speed cycle) whereas the more realistic desired / free flow / cruise speed of 60 km/h gives a geometric delay of around 10 s (acceleration-deceleration delay calculated for a 60 - 0 - 60 km/h speed cycle).

For consistency with the HCM 2010 results, SIDRA INTERSECTION treats delay from the HCM 2010 formula as giving the "control delay" for LOS purposes (as defined in HCM 2010) and will use this delay in calculating the average value of the cycle-average queue which is appropriate as it does not include geometric delay (see below).

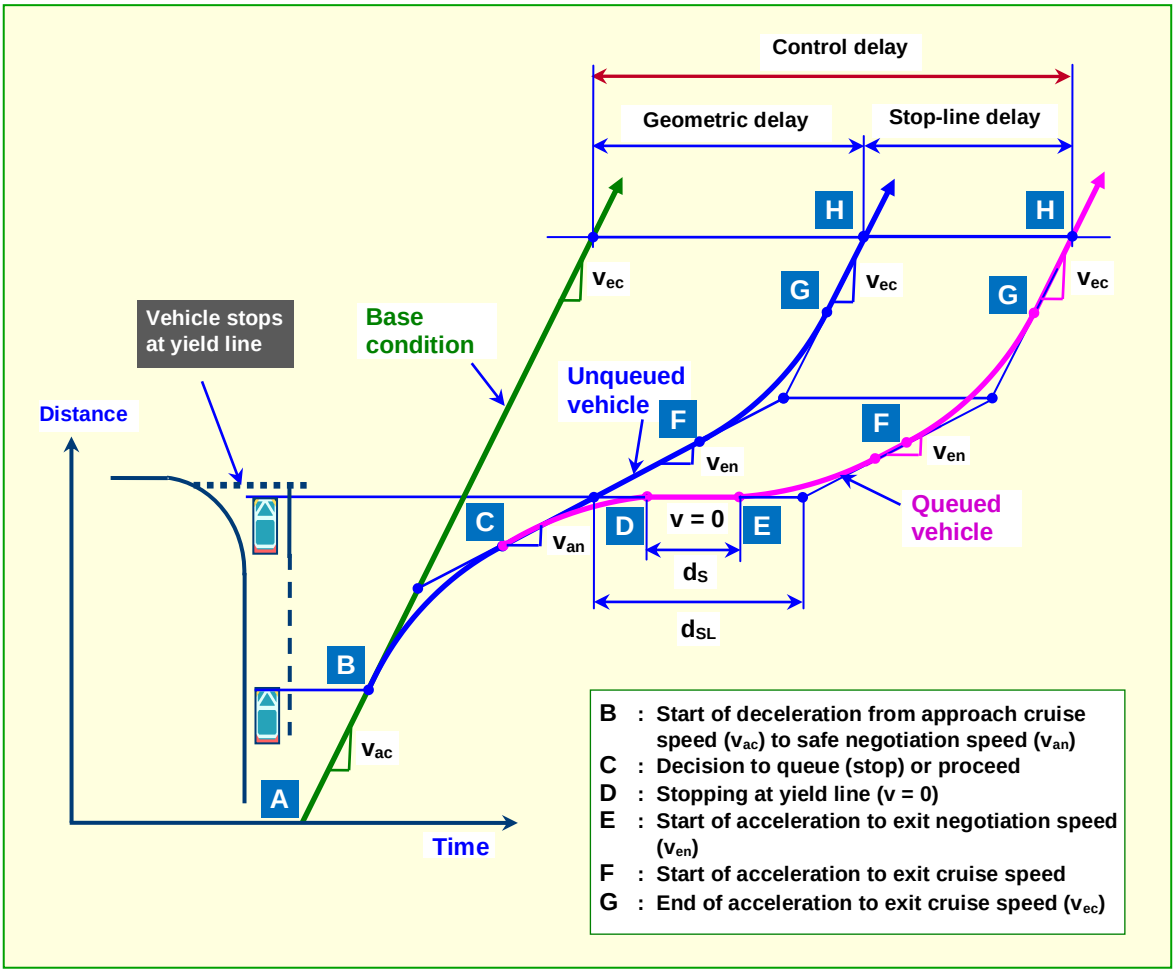

Figure 4 - Definition of control delay, stop-line (queuing) delay and geometric delay

Queue Length

HCM 2010 gives the same formula for *95th percentile queue* for roundabouts and sign-controlled intersections. For roundabouts, it is assumed that this is the 95th percentile value of the ***cycle-average queue***. This is the queue length that incorporates all queue states including zero queues. The average value of the *cycle-average queue* is determined as the product of the average queuing (stop-line) delay per vehicle and the flow rate.

While *back of queue* formulation is included in HCM 2010, Chapter 18 for signalized intersection, back of queue equations for roundabouts or sign-controlled intersections are not available in HCM 2010.

A more useful performance measure is the ***back of queue*** which is relevant to the design of appropriate queuing space, e.g. for short lane design to avoid queue spillback into adjacent lanes, for phasing design to avoid blockage of upstream signals in closely-spaced intersection situations, and so on. The *back of queue* is the maximum extent of the queue that occurs once each signal cycle or gap-acceptance cycle, during green period (signals) or gap-acceptance unblock interval (sign control). Zero queue states are not relevant to the back of queue.

For the reasons of relevance to design practice and for consistency of queue length definitions for signalized and unsignalized intersections, SIDRA INTERSECTION gives average and percentile values back of queue estimates (as well as the ***probability of blockage*** of upstream lanes based on back of queue estimation) in its main output reports for all intersection types. Cycle-average queues are included in some output tables in the queue length tables for information only.

When the HCM delay formula is used, average delay based on this formula is used in calculating *average* value of cycle-average queue when the *HCM Queue Formula* option is also applicable. Percentile queues for cycle-average queue are based on SIDRA standard equations.

Level of Service

The *Level of Service* (LOS) thresholds recommended by HCM 2010 for roundabouts are the same as those for sign-controlled intersections. The use of sign-controlled intersection LOS thresholds may not be appropriate for roundabouts as this would create a bias against roundabouts when compared with signalized intersection treatments. This is of particular concern due to low capacity and high delay estimates from the HCM 2010 model. For this reason, SIDRA INTERSECTION offers options for choice of ***alternative LOS criteria for roundabouts*** including a ***SIDRA Roundabout LOS*** option with thresholds between those for signal and stop-sign control. These alternatives are shown in *Table 6*.

Table 6 - HCM 2010 method for Level of Service definitions based on delay and v/c ratio (for vehicles) with alternative methods for roundabouts

Level of Service for **v/c ≤ 1.0**	Average delay per vehicle in seconds (d)			Level of Service for **v/c > 1.0**
	Signals (*SIDRA standard default for roundabouts*)	SIDRA Roundabout LOS option	Sign Control (*HCM 2010 default for roundabouts*)	All Intersection Types
A	d ≤ 10	d ≤ 10	d ≤ 10	**F**
B	10 < d ≤ 20	10 < d ≤ 20	10 < d ≤ 15	**F**
C	20 < d ≤ 35	20 < d ≤ 35	15 < d ≤ 25	**F**
D	35 < d ≤ **55**	35 < d ≤ **50**	25 < d ≤ **35**	**F**
E	**55** < d ≤ 80	**50** < d ≤ 70	**35** < d ≤ 50	**F**
F	80 < d	70 < d	50 < d	**F**

v/c (demand volume / capacity) ratio, or degree of saturation: v/c > 1.0 represents oversaturated conditions.

The default method for roundabout LOS for the *HCM 2010 model* is the ***same as sign control*** whereas ***same as signalized intersection*** in the *SIDRA Standard* method. Furthermore, a ***LOS Target*** parameter can be used to specify the acceptable LOS level for particular intersection types, e.g. for design life analysis.

Although this issue was discussed during the development of HCM 2010, alternative LOS thresholds for roundabouts should be given further consideration. The fact that roundabouts are significantly easier to negotiate being subject to *yield (give-way) sign* control with only one conflicting stream compared with *two-way stop sign* control with many conflicting streams should be reflected in different LOS thresholds for these two very different types of control. Lower follow-up headway and critical gap values and higher capacities for roundabouts also indicate very different nature of these control types.