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CONVENTIONAL AND UNCONVENTIONAL ROUNDABOUTS: A REVIEW OF GEOMETRIC FEATURES AND CAPACITY MODELS

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ABSTRACT
Road intersections play a key role in traffic management. Modern roundabouts require entering vehicles to yield to the circulating flow, and have proven highly effective in granting high performance levels to both new and redesigned intersections; therefore, their use has widely spread around the world over the years. The choice of the correct shape, size and signage of a roundabout is essential to accomplish the desired results in terms of performance and safety. In order to achieve these goals, designers have moved away from conventional layouts such as single-lane and multilane roundabouts, conceiving more and more unconventional solutions (spiral, turbo and two-geometry roundabouts). Alongside this design evolution, research has been conducted on functional analysis of roundabouts: several authors and authorities have developed capacity assessment models that are suitable for the analysis of unconventional roundabouts, but nowadays no complete review of such models is available. The aim of this paper is to collect descriptions of the main types of conventional and unconventional roundabouts, with a focus on their geometric features and applicable capacity assessment models.
Keywords: conventional and unconventional roundabouts, empirical and stochastic capacity models, roundabout capacity models, spiral and turbo roundabouts.

1 INTRODUCTION

In this paper, an overview has been performed of new, or unconventional, or alternative, roundabout layouts and methodologies suited for such types of roundabout functional analysis.

Unconventional roundabouts typically differ from 'traditional' single lane or multilane ones in one or more design features, as their purposes for application are also specific. In addition, the main reasons for their development rely on disadvantages shown by traditional roundabouts when faced with specific constraints and local conditions. In such a design framework, the traditional geometry layout is often not well suited for attaining the safety and performance stated by standard guideline requirements. Therefore, the designer must recur to an unconventional geometry to convert an existing intersection into a roundabout scheme.

The paper is organized as follows. First, an overview of roundabout layouts has been performed: the characteristics of different types of single-lane and multilane geometries are described; spiral and turbo roundabouts are also presented. Afterwards, in the core section, the most popular and best-suited roundabout capacity models are collected and described. Finally, empirical tests are made for each considered capacity model in its proper application field. Conclusions follow.

2 GEOMETRY

2.1 Single-lane roundabouts

This is the simplest and most traditional layout for roundabouts. It is composed of single-lane entries and exits and a single-lane circulatory roadway ([1], Section 1.3.2). The success of

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single lane roundabouts is directly related to their low number of traffic conflict points when compared to the ones of any uncontrolled or controlled intersection with the same number of branches. Besides, safety is also improved because speeds are generally low due to path curvature and crash angles are reduced in such a manner that crossing conflict points are eliminated and the remainder are merging or diverging conflict points that entail less severe crash conditions. In Fig. 1, conflict points of a single-lane roundabout have compared with those of a yield-controlled four-way intersection.

Thanks to the positive aspects mentioned above, many national regulations have recognized the layout of single-lane roundabouts and have defined guidelines for design, sizing and, in some cases, capacity models. For instance, Italian regulations [2] define geometric features but do not provide nor recommend any capacity model, while American, Swiss and French design guidelines and standards [1, 3–6] include both design requirements and capacity assessment models.

2.2 Multilane roundabouts

In order to cope with the growing traffic demand, roundabouts have evolved to layouts that feature more than one lane at entries, exits and circulatory roadway. Multilane roundabouts grant higher capacities when compared to single-lane roundabouts. On the other hand, a higher number of lanes determine an increase in the number of conflict points, since vehicles get the chance to change lanes in the circulatory roadway, i.e. weaving flows. Consequently, crash rates increase. NCHRP's Informational Guide [1] in Section 5.2.2 explains: 'The additional conflicts unique to multilane roundabouts are generally low-speed side-swipe conflicts that typically have low severity. Therefore, although the number of conflicts increases at multilane roundabouts when compared to single-lane roundabouts, the overall severity (and often the number) of conflicts is typically less than other intersection alternatives'.

Italian design standards [2] allow for two-lane entries and for circulatory roadways up to 9 m (approximately 29 ft) wide, while they do not allow for two-lane exits and they forbid lane markings in the circulatory roadway. These design recommendations highlight

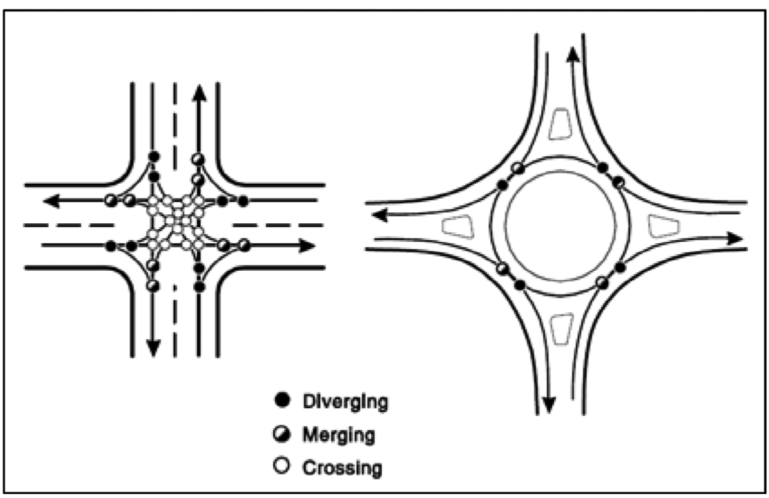

Figure 1: Conflict points in a single-lane roundabout vs. a yield-controlled intersection [1].

the different approach of Italian standards to the subject of multilane roundabouts: while NCHRP's Informational Guide [1] deems necessary to induce vehicles to remain in the correct lane by the use of lane markings, Italian design rule supposes drivers to be able to decide upon the correct trajectory. As a compensative action to this sort of freedom in the circulatory roadway, single-lane exits play a major role in keeping weaving manoeuvers under control.

2.3 Spiral roundabouts

Spiral roundabouts are multilane roundabouts with spiral lane markings. Lane markings are still made of segments of concentric circles, but adjacent circular segments are connected by spiral transitions. The inner spiral transitions originate from the central island: see Fig. 2. The purpose of spiral lane markings is to provide drivers distinct guidance on how they can reach the desired exit without changing lanes [7]. This layout is best suited at large multilane roundabouts because this spiralling out of the lanes avoids drivers, when they are going to exit, to cross multiple lanes on their outer side.

Quoting Homola and Chan [8], this is 'useful in reducing conflict between vehicles at the exits where more than one exit lane is provided'. In order to enter the spiral lane that leads to the desired exit, vehicles need to select the correct entry lane; therefore, entry lane arrangement must be clear and visible in advance. Directional arrows must be placed not only at approaches but also in the circulatory lanes.

A regular multilane roundabout can be turned into a spiral roundabout by modifying circulatory roadway markings. The borders of the central island must be modified too, in order to mark the difference between the circular central island and the inner spiral lane.

British and American design guidelines mention spiral markings in multilane roundabouts, but no definition of spiral roundabout is provided.

2.4 Turbo roundabouts

The term 'Turbo' refers to the shape of the central island which is no longer circular while it is composed of circular sectors with shifted centres. Lanes that evolve around this core

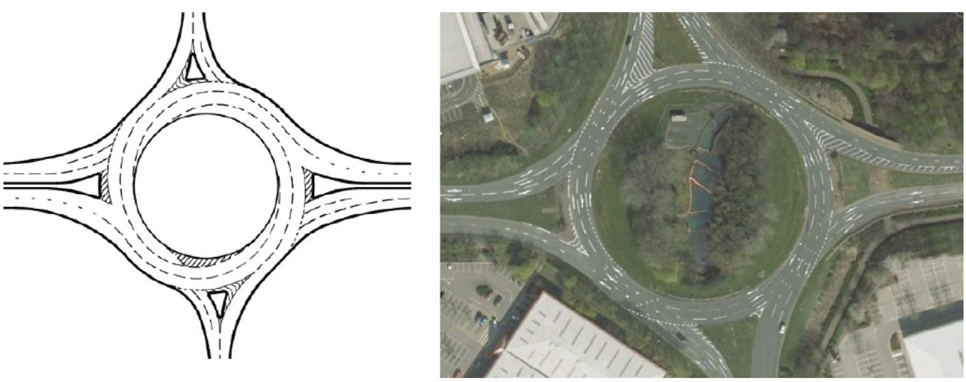

Figure 2: Spiral roundabout layout (left) and the spiral roundabout (right) at the junction of H10 and V7 in Milton Keynes (UK) (left hand circulation).

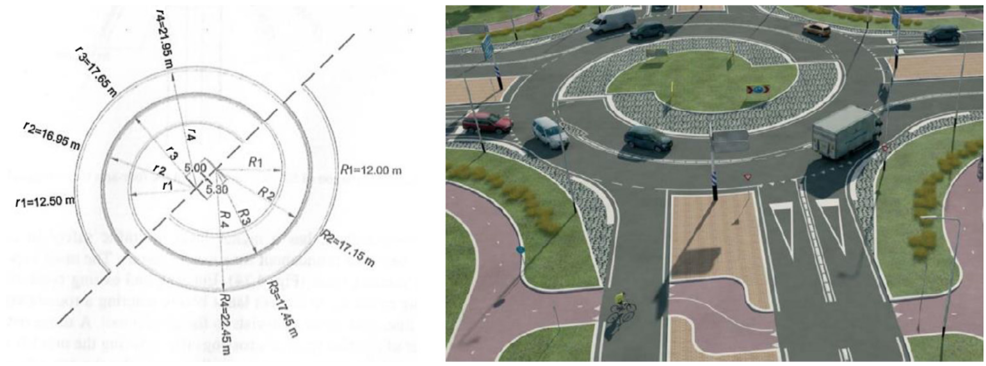

Figure 3: A geometric turbo block (left) and a rendering of a turbo roundabout (right).

have a spiral geometry, since the shift between the centres is nearly equal to the circulatory lane width.

The main concept of turbo roundabouts is to overcome safety issues of multilane roundabouts without decreasing capacity [9]. A turbo roundabout is characterized by lane dividers in the circulatory roadway, at entries and at exits: see Fig. 3. Therefore, traffic streams are channelized according to the selected destination, which determines some consequences: (a) no lane changing on the roundabout; (b) no need to yield to more than two lanes; (c) decrease in the number of potential conflict points.

Unlike multilane roundabouts, where an increase in the number of circulating lanes will lead to an increase of conflict points for weaving, in turbo roundabouts increasing the number of circulating lanes is safer because the lane dividers will prevent lane changing, thus increasing capacity without worsening safety levels. The main rule that designers always have to respect is that every single approach lane must have a dedicated lane in the circulatory roadway. Due to the presence of lane dividers inside the roundabout, designers must make sure that drivers get all the necessary information to select the correct lane in advance.

The geometrical form of turbo roundabouts is fairly complicated, as it is formed by the so-called 'turbo block' (Fig. 3). This last is formed by all the necessary radii, which must be rotated in a certain way, thereby obtaining traffic lanes or driving lanes. The geometric design requires more features as described extensively in Ref. [10].

2.5 Two-geometry roundabouts

A two-geometry roundabout, or 2-G roundabout, is a single-lane roundabout with a circulating roadway whose width is not constant [11]. This results from the shape of the roundabout's outer margin being different from the shape of the central island, respectively elliptic and circular. See Fig. 4. This kind of layout is not explicitly included in any national guideline. Nevertheless, in some practical instances, 2-G type is necessary for attaining both space constraints and safety requirements, i.e. critical conditions for effective deflection of fastest paths.

The advantages of two-geometry roundabouts are the following [11]:

- two-geometry roundabouts require less space, and may be more suited to locations with boundary constraints;

Figure 4: Example of conversion of a 'T' intersection (left) into a two-geometry roundabout. Left: the 'T' junction. Right: the designed 2-G roundabout layout: major axis (a) = 38 m (125 ft); minor axis (b) = 31 m (102 ft); *b*/*a* ratio = 0.82; central island radius = 8.5 m (28 ft); circulating carriageway width = minimum 5.0 m (16 ft)–maximum 8.5 m (28 ft).

- two-geometry roundabouts guarantee trajectory deflection and faster speed reduction with smaller centreline offsets, as may be common with 'T-shaped' intersections;
- two-geometry roundabouts may be more conducive to oversize/overweight large trucks due to varying lane width.

The 2-G type roundabout frequently results in an additional design option, especially suited in the conversion of T-shaped intersections into roundabouts. This is due to its variable circulating carriageway width that makes it able on one side of enhancing trajectories deflection, and on the other side of accommodating high-occupancy vehicles.

3 CAPACITY ASSESSMENT MODELS

The assessment of a roundabout's capacity can be performed by means of different methodologies, either required by national guidelines (i.e. [4]) or suggested by technical guidelines (i.e. [5, 12]), or even incorporated into dedicated software (Section 3.3).

Methodologies for the evaluation of capacity at an entry of a roundabout can be classified as follows:

- Empirical models (regression analysis), determining the statistical influence of geometry and flow rates on the entry's performance, based on regression from data collected at congestion;
- Stochastic models, applying the gap acceptance theory, which is based on the hypothesized behaviour of drivers at a yield line.

Different geometries require the use of different models, since every model is calibrated on data referred to specific conditions of geometry and traffic. In the following sections, a review of the most widely used models is given, in order to determine the most appropriate model for geometries shown above [13].

3.1 Empirical models

In empirical models, the data on which the statistical regression is based only concern geometric features of the roundabouts and flow rates at entries, exits and circulatory roadway. Consequently, when using a model of this kind, the designer must make sure that the analysed roundabout's geometric features and flows be consistent with those from which the model is obtained.

3.1.1 Kimber model

The first capacity model ever conceived for modern roundabouts is Kimber's model, based on a study carried out by a group of researchers of TRR Laboratory (UK) during the 1970s. The following formulas were obtained from statistical regression from experimental observation of roundabouts whose geometric features fall into the ranges shown in Table 1.

The capacity of an entry, expressed in pc/h (i.e. passenger car equivalent per hour), is equal to:

$$C_e = F - f_c \cdot Q_c \tag{1}$$

where:

- Q_c = circulating flow (pc/h),
- K, F, f_c depending on the roundabout's geometry.

Moreover:

$$F = 303\ K\, x \tag{2}$$

$$f_c = 0.21\ K\, t\,(1 + 0.2x) \tag{3}$$

where:

$K = 1 - 0.00347(\phi - 30) - 0.978(1/r - 0.05)$
$t^* = 1 + 0.5/[1 + \exp((D - 60)/10)]$
$x = v + (e - v)/(1 + 2S)$
$S = 1.6(e - v)/L'$

Table 1: Recommended ranges of roundabouts geometric features (Fig. 5) for Kimber's model.

Symbols	Meaning (geometric features)	Observed values	Recommended values
E	Entry width	3,6 ÷ 16,5 m	4 ÷ 15 m
V	Lane width	1,9 ÷ 12,5 m	2 ÷ 7,3 m
L'	Lane flare length	>1 m	1 ÷ 100 m
S	Lane flare slenderness	0 ÷ 2,9 m	–
D	Inscribed circle diameter	13,5 ÷ 171 m	15 ÷ 100 m
ϕ	Entry angle	0 ÷ 77°	10 ÷ 60°
R	Entry radius	> 3,4 m	6 ÷ 100 m

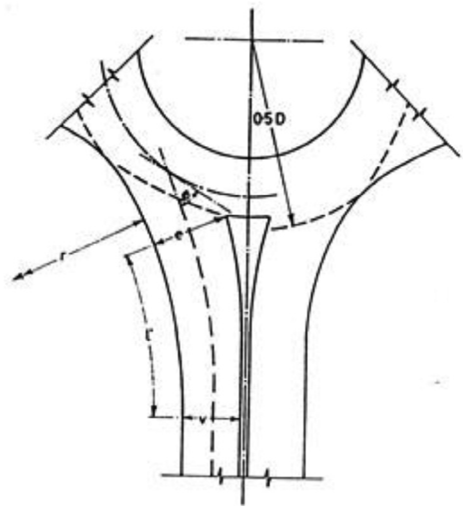

Figure 5: Geometric features for Kimber's model.

The geometric features for Kimber's model are shown in Fig. 5.

3.1.2 French models: SETRA and CERTU

Early studies of French technical agencies CERTU [5] and SETRA [12] provide for empirical capacity models that are suitable for roundabouts located respectively in urban and rural environments. SETRA model is for roundabouts located in rural or peripheral areas with an inscribed circle diameter greater than 45 m.

SETRA model:

$$C_e = (1{,}330 - 0.7 \cdot Q_g) \cdot [1 + 0.1 \cdot (ENT - 3.5)] \tag{4}$$

$$Q_g = [Q_c + 2/3\, Q_u^{*}] \cdot [1 - 0.085 \cdot (ANN - 8)] \tag{5}$$

$$Q_u^{*} = Q_u \cdot \frac{15 - SEP}{15}\,,\ Q_u^{*} = 0 \text{ if } SEP \geq 15 \text{ m} \tag{6}$$

where:

C_e = entry capacity (pc/h),
Q_g = disturbing flow (pc/h),
Q_c = circulating flow (pc/h),
Q_u = exiting flow (pc/h).

All quantities are shown in Fig. 6.

CERTU model was calibrated for roundabouts located in urban or peripheral areas:

$$C_e = \gamma\,(1{,}500 - 0.83\, Q_g) \tag{7}$$

$$Q_g = b\, Q_c + 0.2\, Q_u \tag{8}$$

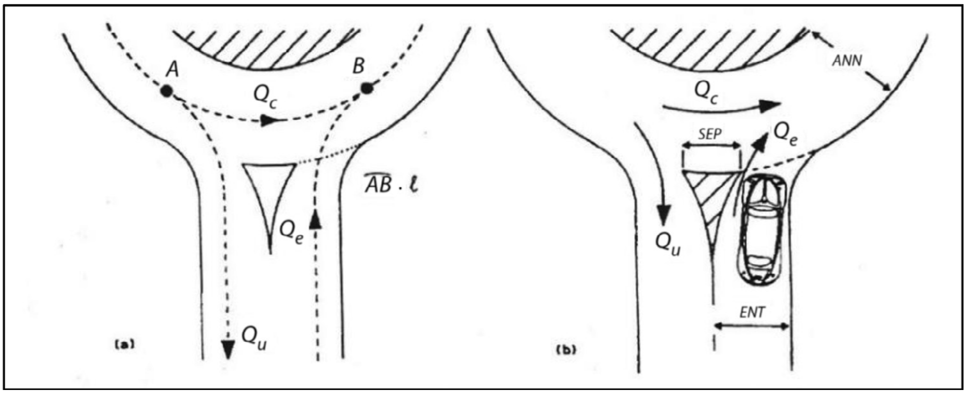

Figure 6: Notations and symbols for CERTU (a) and SETRA (b) models.

where:

C_e = entry capacity (pc/h),
Q_g = disturbing flow (pc/h),
Q_c = circulating flow (pc/h),
Q_u = exiting flow (pc/h),

and:

$$\gamma = \begin{cases} 1 & \text{for one lane entries} \\ 1.5 & \text{otherwise} \end{cases}$$

$$b = \begin{cases} 1 & \text{if } ANN < 8 \text{ m} \\ 0.9 & \text{if } ANN \geq 8 \text{ m and } D < 40 \text{ m} \\ 0,7 & \text{if } ANN \geq 8 \text{ m and } D \geq 40 \text{ m} \end{cases}$$

3.1.3 Swiss model

Swiss guidelines [3, 4] include both design rules that define acceptable geometries and a method for the assessment of capacity and performance of roundabouts. The model provided is suitable for urban 'compact' roundabouts, i.e. roundabouts with an inscribed circle diameter ranging from 22 to 35 m (about 72–115 ft).

$$C_e = 1{,}500 - \frac{8}{9} \cdot Q_g \tag{9}$$

$$Q_g = \beta\, Q_c + \alpha\, Q_u \tag{10}$$

where:

C_e = entry capacity (pc/h),
Q_g = disturbing flow (pc/h),
Q_c = circulating flow (pc/h),
Q_u = exiting flow (pc/h)

and:
α = coefficient for impedance of exiting flow: it is comprised between 0 and 1 and dereases as the distance between diverging and merging conflict points at an entry increases; $\alpha = 0.6$ if the distance is equal to 9 m, and reaches the 0 value when the distance is over 28 m.

$$\beta = \begin{cases} 0.9 - 1.0 & \text{for one circulatory lane} \\ 0.6 - 0.7 & \text{for two circulatory lanes} \end{cases}$$

The model also provides a formula to calculate the average delay (E[w], in seconds) and average queue length (N_{50}, number of passenger cars) at one-lane entries for single circulatory lane:

$$E[w] = \frac{2{,}000 + 2 \cdot Q_c}{C_e - Q_e} \tag{11}$$

$$N_{50} = \mathrm{E}[w]\, Q_e \tag{12}$$

3.2 HCM2016 model

A methodology for the study of roundabouts' performances that develops the probabilistic approach of gap acceptance is that of Highway Capacity Manual, HCM2016 [6]. The roundabout forces vehicles into a right-turn-only circulation; therefore, the theory of gap acceptance for right turns at yield-controlled intersections can apply. Gap acceptance is defined by two parameters:

- Critical gap, t_c, the minimum headway between two consecutive vehicles that is deemed necessary by a yielding driver in order to merge into the main flow. t_c values are comprised between 4.1 and 4.6 s;
- Follow-up time, t_f, the minimum time interval that is deemed necessary by a yielding driver in order to merge into the main flow during the same gap as the previous yielding driver. The t_f values are comprised between 2.6 and 3.1 s.

In case of a Poisson distribution of headways between vehicles circulating in front of the entry, the probability of having a headway $T > t_c$ is:

$$P\left[T > t_c\right] = e^{-t_c \cdot Q_c} \tag{13}$$

where Q_c is the mean value of circulating vehicles (circulating flow or conflicting flow, in passenger car equivalent per hour, pc/h). Therefore eqn (13) describes the availability of useful gaps in the main flow. Accordingly, HCM2016 formula for the entry's capacity (pc/h) is:

$$C_e = \frac{Q_c \cdot \exp\left(\dfrac{-Q_c \cdot t_c}{3{,}600}\right)}{1 - \exp\left(\dfrac{-Q_c \cdot t_f}{3{,}600}\right)} \tag{14}$$

where Q_c = conflicting flow rate (total of circulating lanes) (pc/h).

Once the model is calibrated with the values of t_c and t_f for local conditions (e.g. [6, 12, 14]), then eqn (14) turns into the following equations resumed in Table 2:

Instructions are given by the manual on how to calibrate the generalized model to the project site's local conditions:

$$C_e = A \exp(-B\, Q_c) \tag{19}$$

where: $A = \dfrac{3{,}600}{t_f}$; and $B = \dfrac{t_c - (t_f/2)}{3{,}600}$.

HCM2016 Manual [6] also provides for equations for the average control delay and 95th percentile queue at entries; details are reported in Chapter 22, Section 3.

Highway Capacity Manual's model is applicable to single-lane and multilane roundabouts, with a maximum of two circulating lanes. It is also applicable to spiral and two-geometry roundabouts (provided that the designer calibrate the model to local conditions) since the model only takes into account the driver's behaviour at a yield-controlled right turn, irrespective of the roundabout's radius, entry path curvature or any other geometric feature.

3.3 SIDRA model

Akçelik and Troutbeck [15] showed a significant revision of previous analysis methods. The current method is an extension to previous techniques, introducing the effects of circulating flow, entering flow and geometry on gap acceptance parameters. This method has been

Table 2: HCM2016 entry lane capacity equations for different combinations of entry and circulating lanes (default values).

Number of entry lanes	Number of circulating lanes	Entry lane capacity equation (pc/h)
1	1	$C_e = 1{,}380 \exp(-1.02 \cdot 10^{-3})Q_c$
2	1	$C_{e,RL} = 1{,}420 \exp(-0.91 \cdot 10^{-3})Q_c$ (for both entry lanes)
1	2	$C_e = 1{,}420 \exp(-0.85 \cdot 10^{-3})Q_c$
2	2	$C_{e,R} = 1{,}420 \exp(-0.85 \cdot 10^{-3})Q_c$ (for right entry lane) $C_{e,L} = 1{,}350 \exp(-0.92 \cdot 10^{-3})Q_c$ (for left entry lane)

implemented in the software SIDRA (Signalized/Unsignalized Intersection Design Research Aid), boosting significant development of the intersections and roundabouts analysis [15].

Several capacity models are available in SIDRA:

- Standard Left: for left-hand traffic, and Standard Right: for right-hand one,
- New Zealand and RTA NSW: special settings for local conditions,
- US HCM: implementing HCM models.

Several ranking systems are available for attributing the levels of service; the most interesting for international users are the following:

- Delay & v/c (HCM2010) for US HCM models,
- Delay (HCM2000) for Standard Left, Standard Right, New Zealand,
- Degree of saturation (SIDRA method).

A scheme of the operations performed in SIDRA is reported in Fig. 7. SIDRA could be used for assessing the capacity of all kinds of roundabouts except turbo roundabouts, because the software does not enable the user to force entering flows to merge into a specific circulating lane, whereas the specialization of entry and circulating lanes is the main characteristic of turbo roundabouts. For the purpose of assessing the capacity at entries of a turbo roundabout, the presence of lane dividers inside the circulatory roadway is crucial in order to determine the number of circulating lanes (and the pertaining flow rates) to which entering vehicles must yield.

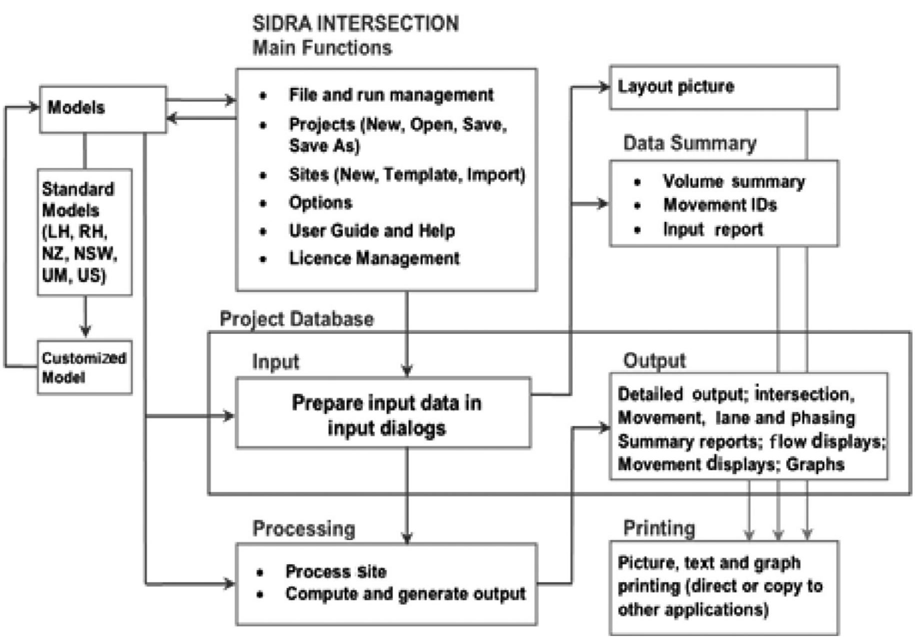

Figure 7: Flow chart of SIDRA intersection operations.

3.4 Bared and Afshar model

Bared and Afshar [16] conducted a study aimed at developing capacity models for roundabouts with two or three lanes in the circulatory roadway. They performed dynamic simulations by the use of VISSIM and simulated several traffic scenarios by varying turning ratios and circulatory lane use. The aim of simulations was to find, for each entry lane, a capacity model as a function of the distribution of flows on the different circulatory lanes. They assumed an exponential relationship between the capacity of the entry and the conflicting flow. They were able to provide formulas for different combinations of number of entry lanes and number of circulatory lanes, covering a wide range of actual cases:

- two circulatory lanes: two entry lanes, three entry lanes
- three circulatory lanes: two entry lanes, three entry lanes

In this paper, we will focus on the models for three circulatory lanes since no other model seems to be currently available for these cases, except SIDRA.

For roundabouts with three circulatory lanes and three-lane entries, they studied 130 cases and obtained the following models.

$$C_{e,L} = \exp\left(7.7054 - \frac{1.1864 \cdot c_1}{1{,}000} - \frac{1.0813 \cdot c_2}{1{,}000} - \frac{0.9479 \cdot c_3}{1{,}000}\right) \qquad R^2 = 0.986 \tag{20}$$

$$C_{e,M} = \exp\left(7.7054 - \frac{0.6758 \cdot c_1}{1{,}000} - \frac{1.1556 \cdot c_2}{1{,}000} - \frac{0.9049 \cdot c_3}{1{,}000}\right) \qquad R^2 = 0.980 \tag{21}$$

$$C_{e,R} = \exp\left(7.7054 - \frac{0.5569 \cdot c_1}{1{,}000} - \frac{0.9044 \cdot c_2}{1{,}000} - \frac{1.0258 \cdot c_3}{1{,}000} + 0.2795 \cdot R_t\right) \qquad R^2 = 0.955 \tag{22}$$

where

$C_{e,L}$ = capacity of left entry lane (pc/h)
$C_{e,M}$ = capacity of middle entry lane (pc/h)
$C_{e,R}$ = capacity of right entry lane (pc/h)
c_1 = flow rate in the innermost circulating lane (pc/h)
c_2 = flow rate in the middle circulating lane (pc/h)
c_3 = flow rate in the outermost circulating lane (pc/h)
R_t = ratio of right turning flow to total entering flow at the selected approach leg.

For roundabouts with three circulatory lanes and two-lane entries, 72 cases were studied and the following models were obtained:

$$C_{e,L} = \exp\left(7.1281 - \frac{1.2403 \cdot c_1}{1{,}000} - \frac{1.2669 \cdot c_2}{1{,}000} - \frac{0.9709 \cdot c_3}{1{,}000}\right) \qquad R^2 = 0.986 \tag{23}$$

$$C_{e,R} = \exp\left(7.1281 - \frac{0.9838 \cdot c_1}{1,000} - \frac{1.0496 \cdot c_2}{1,000} - \frac{1.0352 \cdot c_3}{1,000} + 0.5698 \cdot R_t\right) \qquad R^2 = 0.949 \quad (24)$$

In conclusion, this model can be usefully applied to multilane roundabouts that exceed the number of circulatory lanes suggested by American design guidelines and therefore cannot be calculated by the HCM methodology [6].

3.5 Brilon and Wu basic and modified models

Brilon–Wu model originates from the formula of the 'basic capacity of an entry into a roundabout' [17]:

$$C_e = 3,600\left(1 - \frac{t_m \cdot Q_c}{3,600 \cdot n_c}\right)^{n_c} \frac{n_e}{t_f} \exp\left(-\frac{Q_c}{3,600}\left(t_c - \frac{t_f}{2} - t_m\right)\right) \quad (25)$$

where

Q_c = circulating flow conflicting the entry (pc/h),
n_c = number of circulating lanes conflicting the entry,
n_e = number of entry lanes,
t_c = critical gap (s), t_f = follow-up time (s),
t_m = minimum headway between vehicles travelling in the circle (s).

By the use of this formula, the entry capacity is a function of both geometric parameters and user's behaviour. This formula is suitable for the assessment of capacity of all conventional roundabouts plus spiral roundabout, provided that calibrated parameters are available for local conditions.

For turbo roundabouts, it is necessary to take into account the presence of raised dividers between the circulating lanes. Therefore, a model suitable for turbo roundabouts must be able to distinguish effective disturbing flow from total circulating flow in front of an entry. Mauro and Branco [18] mention a modified version of Brilon and Wu's formula that includes two separate variables to describe circulating flow: Q_{ce}, circulating flow in the outermost (external) lane and Q_{ci}, circulating flow in the innermost (internal) lane. The model is therefore able to take into account the actual amount of circulating flow to which an entry lane must yield to. In this respect, a right entry lane will have to yield only to the flow in the outermost circulating lane, while the left entry lane will have to yield to both circulating lanes because vehicles in this lane are forced to merge into the internal circulating lane. The following equations describe the capacity of right and left entry lanes for a two-lane approach.

$$C_{eR} = 3,600\left(1 - \frac{2.1 \cdot Q_{ce}}{3,600 \cdot n_c}\right)^{n_c} 0.5 \cdot \exp\left(-0.8\frac{Q_{ce}}{3,600}\right) \quad (26)$$

$$C_{eL} = 3,600\left(1 - \frac{2.1 \cdot (Q_{ce} + Q_{ci})}{3,600 \cdot n_c}\right)^{n_c} 0.5 \cdot \exp\left(-0.8\frac{(Q_{ce} + Q_{ci})}{3,600}\right) \quad (27)$$

Table 3: Suggested matches between geometric layouts and capacity models of different types of roundabouts.

Type	Empirical	HCM2016	SIDRA	Bared and Afshar	Brilon–Wu basic	Brilon–Wu mod.	Field of application
Single lane	√	√	√		√		U/P
Multilane	√	√	√	√	√		P/R
Turbo						√	P/R
2-G		√	√		√		U/P

The following parameter values are suggested [18]:

$$t_f = 2.0\ \text{s}\ ;\quad t_m = 2.1\ \text{s}\ ;\ t_c = 0.8 + \frac{t_f}{2} + t_m = 3.9\ \text{s}$$

It must be noted that for turbo roundabouts $n_e = 1$, since capacity must be assessed for one lane at a time. Moreover, $n_c = 1$ for right entry lanes at all approaches, $n_c = 2$ for left entry lanes at approaches 1 and 3, and $n_c = 1$ for left entry lanes at approaches 2 and 4 since there is only one conflicting lane.

3.6 A synthesis on the application fields of roundabout capacity models

Table 3 summarizes the suggested match between geometric layouts and capacity models, according to the recommendations given in the previous sections. Also fields of application are reported: urban area (U), peripheral area (P) and rural area (R).

4 CONCLUSIONS

In the first part of this paper, a review of geometric layouts for roundabouts was provided. The layouts described are single-lane, multilane, spiral, turbo and two-geometry roundabouts. For each layout, the main geometric features were explained, as well as the main functional characteristics. For effective operation of all roundabouts, the assessment of capacity is fundamental. In the second part of this paper, a collection of capacity models was given in order to enable designers to choose the most suitable model for the selected layout.

From a general point of view, the designer toolbox is enriched by some unconventional shapes and new geometric types of roundabouts. These are best suited to cope with special instances and local scenarios, where the traditional circular roundabouts address to limits in safety, or capacity, or both.

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