A COMPARISON OF ROUNDABOUT CAPACITY MODELS

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ABSTRACT
In the present study four roundabout capacity models – Siegloch, Cowan M3-1L, Cowan M3-2L and TRL – are presented and compared against microscopic simulation results. The evaluation framework is centered mostly on the characteristics of the entering and circulating traffic and it is shown that the more popular models – TRL and Siegloch, are unable to generate consistent capacity estimates for the whole range of conflicting flows. The models based on Cowan M3 headway distribution are more robust but still they aren’t sensible to differences in the vehicles destinations, both in the entry and in the circulating traffic. This aspect is also poorly handled by the microscopic simulation model.

KEY WORDS
Roundabout, gap-acceptance, capacity, critical headway, follow-up time, microscopic simulation, Cowan M3

1 INTRODUCTION
Roundabouts are consensually recognised as safe and efficient intersections, being widely used in urban and suburban areas in many countries. Roundabouts offer high capacity levels under a large range of demand scenarios, particularly when compared with other at-level intersections such as priority junctions or even traffic-lights.

The choice of a specific geometric layout may have a significant effect in the roundabout operational conditions and the implementation of new roundabouts is usually preceded by capacity studies both for present and future demand scenarios.

Capacity is generally defined as “the maximum sustainable hourly flow rate at which persons or vehicles can expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic and control conditions” [1]. In the roundabout context, capacity is calculated at approach or entry lane level. Conventional roundabout capacity models are usually classified in two mains groups: empirical (regression analysis) and stochastic (gap acceptance theory). During the last years a new group of models, based on microscopic simulation, became more popular and affordable. However, the calibration and application of microscopic models is not trivial and they are more commonly used to study networks or complex junctions.

The objective of this paper is to present the main principles of each group of analytic models and identify their domain of applicability. The main difference in this research, relatively to similar studies found in the literature, is the use of outputs of microscopic models as reference, instead of field observations. This option may seem unreasonable – after all, the objective of any model is to provide an accurate representation of the real world – but there are good reasons to justify it: a) while analytic models assume steady-state conditions, real world traffic is highly variable with time, and large periods of observations are required to obtain stable average values; b) capacity models should be able to yield consistent estimates for the whole range of the expected circulatory traffic but, in real roundabouts, capacity can only be measured for a limited range; c) in some analytic models capacity is expected to vary according to the distribution of traffic, both at the approach and at the circulatory lanes; this variability cannot can hardly be found in a single roundabout; in alternative, data can be combined from multiple sites, however that option introduces external effects that may be difficult to isolate.

With microscopic simulation it is possible to generate any demand scenario and obtain capacity estimates based on a large number of stable simulation periods. This allows identifying subtle variations that are imperceptible from field observations but that are essential to access the validity of each analytic model.

2 CAPACITY MODELS

2.1 Siegloch

Siegloch’s model [2] is the simplest of a large family of models based on the gap-acceptance theory. All these models have two main building blocks in common: the first block describes the distribution of gaps in the opposing flow; the second describes the usefulness of the gaps to the entering traffic.

The usefulness of gaps is evaluated by a linear or step function that returns the number of vehicles that can move
into the intersection during a given headway (time interval between homolog positions of two consecutive vehicles). This relation takes two parameters: the critical headway \( t_c \), critical gap in older studies) and the follow-up time, \( t_f \). Regarding the distribution of the headways, if one assumes that vehicles move at their desired speeds and independently of each other, then traffic volumes follow Poisson distribution and headways are exponentially distributed. The resulting equation is:

\[
C = \frac{e^{-\phi \left( t_f + t_c \right)}}{t_f}
\]

(1)

where \( C \) is the entry capacity and \( q_c \) is the conflicting flow.

The simplicity of Siegloch’s formula makes it extremely popular, being used in the United States \(^1\), Denmark \(^3\), and Spain \(^4\), among many other countries.

### 2.2 Cowan M3 – Single Lane

The exponential model has two major limitations: it does not describe platooning and it predicts unrealistic short headways. The model gets more distorted as flow rate increases and, consequentially, it can deal realistically only with very low traffic flows \((q < 150 \text{ veh/h})\) \(^5\).

A popular alternative to the exponential model is the Cowan M3 headway distribution. In this model, the headway distribution is described as a mixture of follower and free vehicles headways. It is assumed that the smaller headways of vehicles driving in platoons are represented by a single headway \( \Delta \) (minimum headway), while free vehicles follow a shifted exponential distribution. The model takes three parameters: \( \lambda \) – scale parameter, \( \phi \) – proportion of free vehicles in the traffic stream and \( \Delta \) – minimum headway. Combining this distribution with an acceptance function results in the following capacity equation (Cowan M3-1L):

\[
C = q_c \frac{\phi e^{-\lambda (t_f - \Delta)}}{1 - e^{-\lambda t_f}}
\]

(2)

The estimation of the three parameters is not trivial. It is usual to set a fixed value to \( \Delta \) \((1.8 - 2.0 \text{ s})\) knowing that \(1/\Delta\) is the maximum opposing flow that allows the entry of waiting vehicles. A second relation can be obtained by the method of moments, so as to guarantee the same average flow in the distribution and in the sample:

\[
\lambda = \frac{\phi q_c}{1 - \Delta q_c}
\]

(3)

Finally, an equation relating the observed flow \( q_c \) and the proportion of free vehicles \( \phi \) is required. For this analysis it will be used a bi-linear relation developed by the authors \(^6\), assuming an intra-platoon headway parameter \( \Delta = 2 \text{ s} \):

\[
\phi = \begin{cases} 
1 & \text{if } q_c < 0.178 \\
1.553(1 - 2q_c) & \text{if } 0.178 < q_c \leq 0.5 \\
0 & \text{otherwise}
\end{cases}
\]

(4)

Depending on the model used to obtain \( \phi \), equation (2) can be expressed in different formats. Variations of this model are followed, for example, in Australia \(^7\) and Germany \(^8\).

### 2.3 Cowan M3 – Multiple Lanes

The models described above assume a single priority stream on one lane. In order to account for the effect of multiple opposing lanes, Troutbeck \(^9\) derived the capacity of a minor stream crossing or merging independent major streams, each having a Cowan’s M3 headway distribution with the same intra-platoon headway parameter. A further generalization by Hagring \(^10\) allowed each opposing lane to have independent intra-platoon headways as well as independent gap-acceptance parameters (critical headway and follow-up time). For simplicity sake, in this paper we consider the original formulation for two opposing lanes named Cowan M3-2L model hereafter:

\[
C = \exp \left[ -\left( \lambda_1 + \lambda_2 \right) t_c \right] \frac{(\lambda_1 + \lambda_2) \phi_1 \phi_2}{(1 - \exp \left[ -t_c (\lambda_1 + \lambda_2) \right]) (\phi_1 + \lambda_1 \Delta) (\phi_2 + \lambda_2 \Delta)}
\]

(5)

in this formula the indexes 1 and 2 stand for each of the opposing lanes in the circulatory carriageway; the parameters \( \lambda \) and \( \phi \) should be calculated using formulas (3) and (4).

The Finnish guidelines \(^5\) recommend the use of a variation of this mode (with \( \phi = 1 \)).

### 2.4 TRL Regression Model

This model was developed in the United Kingdom during the late 70’s \(^11\). At that time, it was found that the existing gap-acceptance models, based on Siegloch’s formula, were unable to provide accurate capacity estimates, mainly because they failed to reflect the interaction between roundabout geometry and driver behavior.

Given these issues, the Transport and Road Research Laboratory (TRRL, now TRL) set aside gap-acceptance models and focused research efforts on the development of a regression model based on roundabout geometry and conflicting flow. The development of that model was supported by a very large set of field observations (35 geometries on a test track and 86 public roundabouts) which allowed identifying six variables logically independent and statistically significant: Entry Width \( e \),
Approach Half Width \((v)\), Effective Flare Length \((l)\), Inscribed Circle Diameter \((D)\), Entry Radius \((r)\), Entry Angle \((\phi)\) and Circulating Flow \((q_c)\) (Figure 1).

![Figure 1 - Geometric parameters of the TRL model](image)

The final form of the regression equation is \(^{11}\):

\[
C = K(F - f_c q_c)
\]

Both the capacity \(C\) and the opposing flow \(q_c\) are expressed in Passenger Car Units per hour (PCU/h). The parameters \(K\), \(F\) and \(f_c\) are given by the following set of equations:

\[
S = 1.6(v - e) / l
\]

\[
K = 1 - 0.00347(\phi - 30) - 0.978(1/r) - 0.05
\]

\[
X_2 = v + (v - e) / (1 + 2S)
\]

\[
F = 303X_2
\]

\[
t_p = 1 + 0.5 / (1 + M)
\]

\[
M = \exp\left[\frac{(D - 60)}{10}\right]
\]

\[
f_c = 0.21t_p(1 + 0.2X_2)
\]

This formula yields a linear relationship between the capacity and the opposing flow. The capacity obtained when the opposing flow is null is named “geometric capacity”.

This model is used, among other countries, in the United Kingdom (UK) \(^{12}\) and Portugal \(^{13}\). Alternative linear or exponential regression models are used in France and Italy \(^{14,15}\).

### 2.5 Microscopic simulation

We used a microscopic simulation model (Aimsun, V6.1.4) \(^{16}\) as reference. Microscopic models treat each vehicle, pedestrian, etc., as a unique entity with its own goals and behavioural characteristics, each possessing the ability to interact with other entities in the model. These models capture the interactions of real world road traffic through a series of complex algorithms describing car following, lane changing and gap acceptance.

The use of simulation models for testing purposes requires, naturally, that they are validated at a high confidence level. Normally, this validation must be done at three levels \(^{17}\): the first, known as “conceptual validation”, assures that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is “reasonable” for the intended purpose of the model; the second level corresponds to “computerized model verification”, and assures that the computer programming and implementation of the conceptual model is correct; finally, the “operational validation” guarantees that the model’s output behavior has sufficient accuracy for the model’s intended purpose over the domain of the intended applicability.

In this specific application we were more concerned with the explanatory power of the analytic models than with the absolute accuracy of their estimates and, as such, a highly realistic representation of existing roundabouts (operational validation) was not deemed essential, that is, the model was only required to be validated at the first and second levels. This can be assumed due to the large community of academics and practitioners that during the last decade have been using Aimsun in a large array of applications.

Even tough, it was decided to calibrate the values of two parameters with particular influence in the gap-acceptance process – Reaction Time and Give-Way Time, in order to have capacity predictions similar to field observations of capacity. Default values were kept in the majority of the remaining parameters.

### 3 ASSESSMENT FRAMEWORK

#### 3.1 Effect of the opposing flow

The objective of first analyses was to evaluate how the analytic models are able to predict the capacity of an approach lane in a single-lane roundabout with four legs. This roundabout was assumed to have normal geometrical parameters \((v = 3.5\ m, e = 4.0\ m, l = 20\ m, \phi = 30^\circ, r = 20\ m\) and \(D = 40\ m)\) and was modeled in Aimsun as a sequence of T-junctions. A very large demand flow was generated at the south centroid in order to guarantee continuous queue upstream the south entry (in the S-N direction) while increasingly opposing flows were generated at the west centroid, in the W-E direction. It was obtained a geometric capacity of 1733 veh/h and a minimum capacity of approximately 90 veh/h for opposing flows above 1600 veh/h (the capacity never dropped to zero because drivers are assumed to force their entry into the roundabout when their waiting time exceeds a given “patience threshold”).

From the graph it is evident that, given a suitable set of gap-acceptance parameters (in this case, \(t_c = 3.9\ s, t_f = 2.1\ s)\) it is possible to fit Cowan M3 model to the entire range of simulated capacities. A similar adjustment cannot be achieved with the Siegloch model, even when unrealistic
parameters are assigned to the model; likewise, it is impossible to obtain good estimates in the whole range of capacities when using the TRL regression model, due to its linear shape.

3.2 Effect of traffic split in the opposing lanes

This second analysis aims to identify the applicability of the analytic models to predict the capacity of two-lane roundabouts under different traffic splits in the circulatory lanes. In order to minimize the number of external factors involved, it was assumed that only the left approach lane could be used. This action prevents vehicles from deceleration and even stopping upstream the entry, in order to change lane, which would violate the principle of continuous queuing and lead to wasted entering opportunities. In real roundabouts the lane changing effect is reflected in the value of the follow up time (gap-acceptance models) or in the geometric capacity (regression models), leading to a capacity reduction.

Similarly to the previous analysis, a very large demand flow was generated at the south centroid (S→N direction, see Figure 3) while different demand levels at the opposing lanes (near/far) were simulated by varying the demand at the west and north centroids. As traffic from the west centroid is legally allowed to use both circulatory lanes, a “lane rule” was introduced forcing the use of the near lane. This was not necessary for traffic originated at north centroid as it can only use the far lane.

For each opposing flow demand level, three traffic splits were simulated ($p = 0\%$, $p = 25\%$ and $p = 50\%$, where $p$ is the percentage of the total opposing traffic using the near lane). The results of the simulation are presented in Figure 4 and compared with the estimates of the multilane Cowan M3 model for the parameters $t_c = 4.7$ s, $t_f = 2.3$. The single-lane Cowan M3 model corresponds to the multilane model when $p = 0\%$.

The graph illustrates that the capacity is higher when opposing traffic is equally divided among the circulatory lanes. In this case bunching is least and bunch overlap is greatest for a given total major flow rate.

This behavior is well adjusted by the multilane Cowan M3 model. Simple models, such as Siegloch’s or single-lane Cowan M3 can also be used to estimate capacity in multilane roundabouts assuming total traffic superimposed in one lane, however they will considerably underestimate capacity when opposing traffic is distributed in the circulatory lanes.
3.3 Effect of the demand directional split

In this last analysis the combined effect of the direction split both in the entry and in the opposing flow is evaluated. The total opposing flow at the south approach was set to a constant value (1200 veh/h) and all possible combinations of destinations were generated in 10% steps. Each of these combinations state the following proportions of the total opposing flow:

a) using the far lane, heading north (N→N)
b) using the far lane, heading east (N→E)
c) using the near lane, heading east (W→E)

Regarding the entry flow, and similarly to the previous point, the disturbances associated to lane changing maneuvers were avoided by allowing entry traffic to use only one approach lane (the right one, in this case). Two demand scenarios were considered: in the first (Figure 5) all entry drivers are heading north, in the second all entry drivers turn right to east direction (Figure 6).

From the first graph one can identify two extreme cases: the minimum capacity, when all opposing vehicles are heading east using the near lane, and the maximum capacity, when there are only U-turns. In this case the trajectories do not overlap and entries are made independently of the opposing flow. This is clearly a limitation of the simulator because in real world entry drivers aren’t fully aware of vehicles’ destinations and many will wait until they realize that the entry is safe.

This behaviour is particularly relevant when all entry vehicles are turning right (second graph). In this case the simulator assumes that only the W-E traffic using the near lane conflicts with the S-E traffic and predicts maximum capacity for the remaining cases. Once again, this is not true in most real world cases because waiting drivers aren’t aware of vehicles destinations or if they decide to change lane at the exit.

Despite these limitations, it becomes clear that the destinations of both entry and opposing traffic are relevant in capacity calculations. Unfortunately, this information isn’t explicitly considered by any of the analytic models presented.

4 DISCUSSION

There seems to be three main reason to justify the widespread use of simplified models: a) lack of evidence from field observations – as referred, typical capacity data from real roundabouts is highly scattered, making it difficult to identify real trends; b) historical reasons – when capacity models based on Cowan M3 distribution were obtained, a large investment had already been made in the UK to develop regression methods and other countries have followed this approach; c) natural preference of practitioners for simple models – one of the reasons that lead the TRRL to adopt a linear regression approach was because, according to Robert Ashworth, it was “thought that exponentials were too clumsy to incorporate into a design formula. Pocket calculators were not in general use at that time and the simpler linear approach was favoured”.

The simulation results clearly indicate that some characteristics of the conflicting traffic are essential to
explain the variation in capacity estimates. Therefore, the adoption of generalized formulas such as Hagring’s (5), seems now natural. There are, however, some important issues that should be addressed to improve its explanatory power: the relation between geometric characteristic and roundabout capacity is not explicitly integrated in the formula; there is no consensus about the best way to estimate the parameter “proportion of free vehicles” $\phi$; the formula is insensitive to the destination of entry and opposing vehicles at multilane roundabouts. Finally, the estimation of gap-acceptance parameters for this formula is particularly complex, especially if it is assumed that they are different for each of the circulatory lanes.

5 CONCLUSION

In this paper it was presented a comparative analysis of four roundabout capacity models. It was found, by comparison against microscopic simulation, that the ones more widely used – TRL linear regression and Siegloch – are unable to generate consistent estimates along the complete range of possible circulating flows. The best fit was obtained with Hagring’s model based on Cowan M3 distribution. Not only this model generates accurate estimates for the complete range of opposing flows, but it also satisfactorily describes the effect of traffic distribution in the opposing lanes, predicting higher capacity when opposing traffic is equally distributed in the major lanes.

However, none of the analytic models takes explicitly in account the destination of both entry and circulating vehicles. The microscopic model can’t cope satisfactorily with this aspect, as well. It was concluded that, although generalized gap-acceptance models based on Cowan M3 distribution are recommended, further research is required to improve their applicability.

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