Traffic & Transportation

A Mixed Method Approach for Modelling Entry Capacity at Rotary Intersections

Antonio PRATELLI[1], Lorenzo BROCCHINI[2], Reginald Roy SOULEYRETTE[3], Teng WANG[4]

Original Scientific Paper
Submitted: 15 Nov 2024
Accepted: 11 Mar 2025

[1] antonio.pratelli@unipi.it, University of Pisa, Department of Civil and Industrial Engineering
[2] Corresponding author, lorenzo.brocchini@gmail.com, University of Pisa, Department of Civil and Industrial Engineering
[3] souleyrette@uky.edu, University of Kentucky, College of Engineering
[4] Teng-Wang@uky.edu, University of Kentucky, College of Engineering

This work is licensed under a Creative Commons Attribution 4.0 International Licence.

Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

Rotary intersections, known as old traffic circles, require vehicles entering from branches to yield to circulating traffic. Upon entering, vehicles travel around a central island and exit toward their desired branch, generating merging and diverging conflicts at entry and exit points. Rotary capacity models are focused on the weaving manoeuvres within the circular roadway sections, associating capacity with the maximum traffic flow rate of each weaving segment. This paper introduces a novel approach combining modern roundabouts capacity models with the old rotary ones. In particular, the present study proposes a mixed approach based on an iterative process that combines the English TRRL model, which is suited for the old rotaries and based on short weaving sections capacity, with the features of the HCM-7th entry capacity model of the modern roundabouts, which is based on the circulating-traffic priority rule. Such an approach is rooted in the total capacity criteria and traffic conditions where all roundabout entrances reach congestion simultaneously. Compared to the past, this new approach makes entry performance estimation, such as average delay and queue length, bridging the gap between outdated and current methodologies in the field of rotary intersection design and assessment.

KEYWORDS

TRRL rotary capacity model; HCM roundabout model; roundabout total capacity; combined iterative approach; rotary intersections capacity and performances.

1. INTRODUCTION

Rotary intersections are classified as a special type of unconventional roundabouts and often they are also called old traffic circles or old rotaries. This terminology arises from the fact that early roundabouts, developed in the 1960s, implemented the yield-at-entry rule, distinguishing them from today's modern roundabouts. After World War II, vehicles and highways grew fast and rotary technology was mainly developed in the United Kingdom. British researchers experimentally saw that rotary intersections were safer than crossroads [1]. However, the "priority-at-branch" rule was abandoned in the United Kingdom since the late 60s to rectify problems associated with this old traffic circles or rotaries. Indeed, such a rule applied to all circular intersections that imposed entering flow to give way to circulating flow often led to negative experiences due to locking up partially or entirely the circle as traffic volumes increased.

Therefore, the modern roundabouts conceived to avoid the above-mentioned problems by the new rule that requires entering flow to give way to circulating flow. This latter prevents any growing queue due to locking up by not allowing vehicles into the circle and making this as the distinguishing characteristic of the modern roundabouts. Nevertheless, there are still today some circular intersections somewhere in the world that adopt the "old" priority rule and by consequence, these are called old rotaries.

As traffic flow reached some critical values, around 3,000 pce/h [passenger car equivalent for an hour], circling vehicles stopped by inner traffic and queues arose in the circle till to block the upstream exits. This way, the rotary fell into "grid-lock" conditions, with its capacity dropped to zero and no vehicle could enter or exit the circle. Therefore, the design practice to cope with the above "capacity-drop" phenomena was addressed to large rotaries, with huge circle dimensions and diameters over 100 – 140 metres or even more. These large rotaries were crossed by high-speed trajectories that led both to low road safety conditions and resulted in very few gains of capacity. The matter was that entering vehicles could not easily merge in the circling traffic flow due to the fast vehicles already entered in the rotary from other converging branches and moving around the central island to weave out of the circle into their desired exiting road. This creates merging and diverging conflicts among any entry and its successive exit, i.e. a rotary short section, due to weaving traffic flows. Therefore, rotary capacity models are usually based on the weaving of the different movements in any section of the circle, and the maximum rate of flow value is then related to each weaving section of the rotary. At the beginning of the 1950s, the Transport and Road Research Laboratory developed a research project based on weaving theory to set up a rotary capacity predictive model. This latter is known as Wardrop's, or TRRL model, and to date, it is extremely popular and largely used, especially by Countries belonging to the Commonwealth, such as India, South Africa and Nigeria [2].

In any case, the TRRL capacity model helps the designer in geometry tasks, but it does not give any information referring to and adequately describing the performance of rotaries [3]. Starting from the early 1970s, several nations in the world, spanning from some European countries to Australia and even Britain, proposed technical guidelines where the rule of yield-at-entry was reversed in its priority to circulating vehicles. The main expected effects were both in smaller dimensions with less need for spaces and increased capacity in avoiding any circle "capacity-drop" because queues have been shifted on branches. Since the mid-1980s, modern roundabouts with priority for circulating traffic have become increasingly common, and a large amount of experimental performance data has become available for each entry. As a consequence, many mathematical models, dealing with entry capacity and delay, were developed. Nowadays, one of the crucial steps in modern roundabout design practice is performance evaluation, and this last appraisal is also at the core of any project for converting old rotaries into modern roundabouts [4].

Moreover, on one side, rotaries, as quoted above, are often designed and built in some world countries today, applying the TRRL model without any possibility of performance evaluation. In addition, there are instances where national guidelines require a short weaving section approach for modern roundabouts with exceptionally large diameters at intersections. This last case, for example, is referred to the current Italian intersection guidelines [5], where it is required a short weaving section model application for any roundabout diameter exceeding the threshold value of 50 metres. Nevertheless, the same Italian guidelines recommend that any intersection should be designed concerning its performance evaluation. Then, faced with the above framework, the following proposed model relies on the main goal to extend the capabilities of the TRRL rotary model, very well-suited for a short weaving section analysis, by combining it with one of the most popular modern roundabout capacity models embedding delay and level of service evaluations, i.e. HCM-7th model. The HCM-7th Edition refers to a procedure for evaluating the operational performance of modern roundabouts which incorporates a series of models relating to each single specific combination in the number of conflicting lanes at the entrance and in the circulating carriageway in front of the entrance itself. In particular, the mixed model approach [6] has been used to calculate the so-called total capacity of a rotary [7] from two different points of view.

First, considering the evidence that a rotary is completely blocked when all weaving sections are simultaneously oversaturated and therefore no vehicle can enter or exit any branch. Second, at the same time and as a direct consequence of the rotary block, the vehicles are queuing up at all the entrances, where capacity is reached. By combining the above two pieces of evidence, one can write an equation for each branch, where its respective entry capacity is unknown. This leads to a system of linear equations, the solution of which is each entry capacity value of the rotary. Therefore, the present research work begins by highlighting the main features of the mixed method approach. Then, it is followed by a brief description of the two capacity models chosen to be combined, namely the TRRL rotary model based on weaving sections capacity, and the HCM-7th model for modern roundabouts entry capacity. Subsequently, it is explained what is meant by the total capacity of a roundabout and how the idea behind this research work started from it. Hence, it has shown how the rotary entry capacity can be obtained by solving through the Gauss-Seidel algorithm the linear n-equations system, one equation for each of the n-branches belonging to the rotary. To provide additional context for the theoretical framework, the last chapter discusses relevant case studies from both Italy and the US.

This analysis underscores the importance of a comprehensive performance evaluation, especially when considering future conversions and the broader implications on traffic management systems. In the end, the importance and innovation of this research, along with future developments, is discussed in the conclusion section.

2. METHODOLOGY

This section first reviews the mixed method approach, emphasising its role in combining multiple evaluation models to improve the assessment of roundabout capacity. Then, the TRRL rotary model and the HCM-7th model are discussed separately, highlighting their distinct methodologies and applications. Finally, the section concludes with an analysis of the total capacity, which integrates the findings from both models to provide a comprehensive overview of intersection performance, particularly for unconventional roundabouts.

2.1 Mixed method approach

Over the past two decades, several research papers have been published addressing the concept of incorporating different models to generate a single valuation approach that often results in a deeper and more comprehensive valuation than distinctive conventional procedures relying on only one method [6]. A mixed method approach combines two or more assessment methods, potentially at every stage of the evaluation process.

Mixed method evaluations may use different data sources, for instance incorporating results drawn from both practical case studies and random experiments. For instance, they may include different procedure techniques, such as demand forecasting models processing the same database. In short, a mixed-method evaluation involves the systematic integration of different kinds of data and/or approaches, usually suited and drawn from different fields. Among the cases in which mixed method approaches are useful to improve an assessment task, there is when a single evaluation aspect can be coped with more than one solution method. Moreover, several advantages can be gained by using a mixed method for combining models or improving data collection strategies.

For example, one mixed method approach can be used to help guide the use of another method or to better explain the results obtained from another one [8]. In the limits of this study, the mixed method approach reported below was applied in a complementary way, coupling two different models, both simultaneously, and at various extents dealing with rotary capacity.

Nevertheless, and anyway always at least within the limits of the present experimental study, such a parallel approach requires an easy computational effort and the total implementation time of the mixed methodology can be affordable in any practical instance. Simply put, this research incorporates several methods into a single model which may lead to better estimates and broader evaluations of rotary intersections. Combining capacity models for old rotaries and modern roundabouts, the proposed model offers a more accurate and effective assessment of the performance characteristics of the rotaries themselves.

2.2 TRRL model

Although the capacity calculation with the TRRL model [9] is referred to the old rotaries, to date there are various instances where the intersections' national guidelines ask for the utilisation of modern roundabouts too.

Among these instances are the current Italian intersection guidelines [5], where a short weaving section model application is required when the roundabout diameter value is greater than 50 metres, i.e. about 150 ft. For this last reason, roundabouts exceeding such threshold are classified as "unconventional" and they must be calculated with the principle of weaving flows between two contiguous arms, i.e. a section.

Anyway, old rotaries are usually still designed and built in some countries, such as India, where the TRRL capacity model is largely applied [10]. The Transport Road Research Laboratory, or TRRL model, also known as the "English Method", consists of a specific computation system for the sizing and verification of the different individual sections between consecutive entrances of a traffic circle which are precisely considered as short sections of exchange. The TRRL formula is the following *Equation 1*:

$$Q_{MAX} = \frac{A \cdot w \cdot (1 + {}^{m}/_{w}) \cdot (1 - {}^{P}/_{3})}{(1 + {}^{w}/_{L})} \tag{1}$$

where:
— Q_{MAX} is the maximum hourly flow rate that can be accommodated in an interchange section [vehicles/h];
— A is a constant (usually equal to 354);
— w is the width of the road section in the interchange area [m];
— m is the average width at the entry section, calculated as $m = (m_1 + m_2)/2$ [m];
— L is the length of the section [m];
— P is the ratio between the interchange flow and the total flow in the section.

As noted, the formula above calculates the value of the maximum hourly flow rate Q_{MAX} that can be accommodated in an interchange section. Regarding the parameter P, it represents the proportional contribution of the interweaving current $Q_w = (b + c)$ to the total traffic flow $Q_T = (a + b + c + d)$ in the section. *Equation 1* overestimates the flow rate for small and compact roundabouts (when the flow rate value is lower than 4,000 vehicles/h), therefore, in these cases, the calculation must be repeated assuming the reduced value of 302 for the constant A. The weaving proportion P is defined with the *Equation 2*:

$$P = \frac{Q_w}{Q_T} = \frac{(b+c)}{(a+b+c+d)} \tag{2}$$

where a, b, c and d are the values associated with their respective traffic flows in the weaving section according to the scheme established in *Figure 1*.

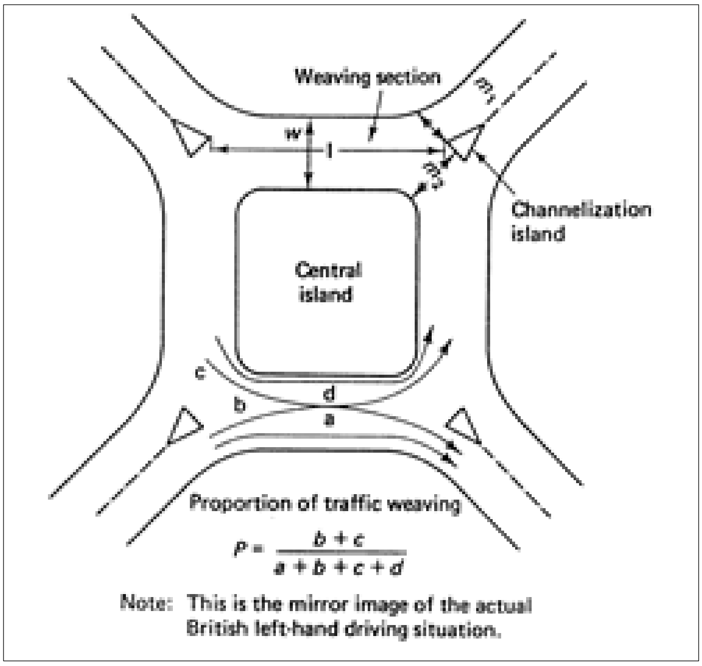

Figure 1 – Scheme of the method of the TRRL – Transport Road Research Laboratory, also known as the "English Method" [9]

The values obtained from *Equation 1* of the TRRL model are obviously the maximum flow values of the different weaving sections, which correspond to congestion conditions, with long queues and modest outflow speeds, around 16 km/h. To avoid considering congestion, the following condition, *Equation 3,* must be satisfied each time for each exchange section:

$$Q_T \leq \eta \cdot Q_{MAX} \qquad (\eta = 0.80 \div 0.90) \tag{3}$$

2.3 HCM-7th model

The Highway Capacity Manual (HCM) is the fundamental and worldwide applied technical reference dealing with traffic engineering tasks for concepts, performance traffic measures and operational techniques, both in design and road facility performance appraisal.

Its 1st edition was published in 1950 and it is updated regularly based on new research supported by the Transportation Research Board (TRB). Today HCM reached the 7th Edition, released in 2022 [11].

In the Highway Capacity Manual Reference Guide [12], roundabouts were defined as "intersections with a generally circular shape characterised by the yield on entry and circulation (counter clockwise in the United States) around a central island".

Also, it is always specified in the Reference Guide that roundabouts have been used successfully all over the world and are being used more and more in the US, especially since 1990. It is well known that the entry capacity of a roundabout can be determined through two different approaches: theoretical models, based on the "gap-acceptance" theory; empirical models, obtained by regression on experimental data.

The procedure for calculating the entry capacity of roundabouts found in the HCM manual belongs to the first group, i.e. the theoretical models as it is based on the "gap-acceptance" theory.

In detail, the value of the parameters of the HCM prescription derives from experimental observations carried out in the US. In HCM-7th, there are different capacity formulas depending on the different combinations between the number of lanes at the entrance of a branch and the number of lanes present in the ring in front of the entrance itself.

Furthermore, to apply the HCM-7th calculation procedure, the values of the critical headway and follow-up headway parameters calibrated should be used.

There are several studies that deal precisely with the estimation of parameters A and B of the HCM model through "local calibration" [13]. The general HCM formula for calculating the roundabout entry capacity C_e, function of the circulating flow Q_c, is the following *Equation 4*:

$$C_e = Ae^{(-BQ_c)} \tag{4}$$

where A and B are parameters to be specified with respect to:
— location (country or region);
— lane: single, right or left;
— lane number in the roundabout ring: 1 or 2;
— critical interval tc (default or local calibration);
— progress follow-up value tf (default or local calibration).

Once the entry capacity of the analysed roundabout has been obtained, it is also possible to calculate the corresponding level of service or LoS.

The concept of level of service appeared on HCM in 1965. It was formally defined as a qualitative single measure of the combined effect of several factors, which include density and speed, delay and travel time, traffic queues and freedom to manoeuvre, urban and rural and recreational location.

The level of service is referred to as a scale of six letter designations, from A to F, where each level represents a range of operating conditions, and each level is defined in terms of threshold values linked to a set of some selected driver perceived parameters.

The levels of service cover the whole range from free flow to congestion, and span from best quality of vehicle operation, when any vehicle is not significantly affected by the presence of other vehicles, to worst quality of traffic flow designated by frequent flow interruptions when vehicles move in stop-and-go conditions, suffering long delays, and encountering queued traffic.

The average waiting time, or delay, for each lane of a roundabout entry, can be calculated by *Equation 5*:

$$d = \frac{3600}{C} + 900T(x - 1 + \sqrt{(x-1)^2 + \frac{(3600/C)x}{450T}}) + 5 \tag{5}$$

where:
— C is entry capacity (vehicles/h);
— x is Q/C ratio;
— T is the analysis time period, usually taken of 15 min (1/4 of 1 hour), therefore equal to 0.25.

As mentioned, with the average waiting time, delay "d", it is possible to determine the LoS, using the following *Table 1*:

Table 1 – LoS values based on the average delay

Delay "d" [s/veic]	LoS
0÷10	A
>10÷15	B
>15÷25	C
>25÷35	D
>35÷50	E
>50	F

2.4 Total capacity

Before defining the total capacity of the roundabouts [7], it is appropriate to clarify why the idea on which this research work is based started precisely from this parameter. As previously explained, there are various guidelines and regulations in various countries of the world which indicate to the calculation of the so-called "unconventional" roundabouts in ways other than those in the HCM manual.

In particular, in the current Italian intersection guidelines [5], roundabouts larger than 50 metres in diameter are all classified as "unconventional" and must be calculated with the principle of weaving flows between two contiguous arms (TRRL model).

Several researchers, therefore, thought of comparing the 2 models (HCM-7th model and TRRL model) for the same type of unconventional roundabout. For example, in a study on a particular type of unconventional roundabout (two-geometry roundabouts [14, 15]).

In the research cited, the conclusions that have been drawn are that the results obtained from the calculation with the HCM method are quite similar to those obtained through the English TRRL method. The rotary entry capacity, which is the goal of this study, was therefore taken into consideration by a mixed method approach to combine two capacity models linked to each other by the fact each one can be referred to as a common resulting effect, i.e. the rotary total capacity [7].

The total capacity of a rotary is defined concerning a given traffic distribution scenario and represents the sum of the values of the incoming flows from each branch which simultaneously determine the congestion of the branches themselves.

In particular, the total capacity of a rotary represents the upper limit of the intersection itself to dispose of traffic when there are queues at each of its branches. It is given by the sum of the capacity values that occur in the various entrances when these are all simultaneously in congestion, i.e. they are all at capacity and with queues.

Starting from what has just been described and from the two following evidence: a roundabout is completely blocked when all the weaving sections are simultaneously oversaturated and therefore no vehicle can enter or exit any branch; at the same time and as a direct consequence of the roundabout block, the vehicles are queuing up at all the entrances, where capacity is reached; in the next paragraph, the solution algorithm that the authors have arrived at will be illustrated.

3. SOLUTION ALGORITHM

As said above, the TRRL method is not able to calculate the capacity of any single entrance, by consequence, it is not possible to calculate any performance indicators, such as the average entry delay and the queued vehicles at the entrance.

Each of these last two performance indicators directly depends on its entry capacity through the respective two expressions, which are as follows, *Equations 6* and *7*. The first is the delay formula of Kimber and Hollis [16], while the second one is the practical estimation of the 90th percentile of queue length:

$$E[w]_i = \frac{2000+2Q_{ci}}{C_{ei}-Q_{ei}} \tag{6}$$

$$L_{90}^{i} = 2 \cdot Q_{ei} \cdot E[w]_i \tag{7}$$

where:
- $E[w]_i$ is the estimate of the average delay time at entry *i*;
- Q_{ci} is the circulating flow at entry *i*;
- C_{ei} is the capacity of entry *i*;
- Q_{ei} is the flow rate of entry *i*;
- L_{90}^{i} is the estimate of the average queue length at entry *i*.

More in general, the previous *Equation 4* of HCM-7th represents the capacity of an entry lane when Q_c is the conflicting flow rate on the lane in front of the entrance itself. *Equation 4* is strictly referred to as modern roundabouts, and it is not suitable for rotaries. However, one way to obtain an estimate of the capacity of an entrance starting from the TRRL method can be to exploit the concept of the total capacity of a roundabout, although this is not obtained simply by adding the capacities calculated for each single entrance concerning a given $M_{O/D}$ matrix of traffic on the intersection.

Instead, the total capacity, sometimes also called full capacity [7], of a roundabout is defined as the sum of the obtained values for a given traffic $M_{O/D}$ matrix and reached when the entrances are all simultaneously in congestion.

Any weaving section of a rotary becomes congested when the total flow Q_T travelling along the section reaches the value of Q_{MAX}, which is precisely given by *Equation 1* of the TRRL method. Now, assuming that at the same time, all the rotary entrances are also simultaneously at their respective capacity, then the rotary is at total capacity.

By consequence, at the same time again the corresponding flow rates traversing any single weaving section of the rotary derive from this same entry capacity distribution. All these last considerations are transferred to the following model, which begins with the evidence that in any single weaving section (*i*, *i+1*) both the total flow $Q_{T_{i,i+1}}$ and the weaving flow $Q_{w_{i,i+1}}$, derive from the flow amount entering the rotary from the various branches.

In the following *Equations 8–12,* the weaving sections considered are n and the generic texture section is *i*, *i+1*.

$$Q_{MAX_{i,i+1}} = f\left(P_{i,i+1}\right) = f(Q_{T_i}, Q_{T_{i+1}}, Q_{S_i}, Q_{S_{i+1}}) \tag{8}$$

then, when the rotary reaches its total capacity, it is possible to write both:

$$Q_{T_{i,i+1}} = f\left(C_{e_i}, C_{e_{i+1}}, \dots, C_{e_n}\right) \tag{9}$$

$$Q_{w_{i,i+1}} = f\left(C_{e_i}, C_{e_{i+1}}, \dots, C_{e_n}\right) \tag{10}$$

then, consequently:

$$P_{i,i+1} = f\left(C_{e_i}, C_{e_{i+1}}, \dots, C_{e_n}\right) \tag{11}$$

and finally:

$$Q_{MAX_{i,i+1}} = g(C_{e_i}, C_{e_{i+1}}, \dots, C_{e_n}) \tag{12}$$

leading to a system of linear equations, one for every one of the *n* sections forming the rotary. The unknowns of this system of n linear equations that bring together the two capacity models, that of the TRRL with the HCM-7th, are the capacities of the different n entries of the n branches of the rotary. For the solution of the system of n linear equations in n unknowns, representative of the proposed model, it can be solved with the iterative method of Gauss-Seidel. For the safety of simplicity, the algorithm application is described through the instance of a three-branch rotary as follows. The procedure is as follows.

Stage 1

The HCM-7th model is used for the rotary so as to be able to calculate the total capacity of the same and in particular the values of the capacities $C_{e1}*$, $C_{e2}*$ and $C_{e3}*$ which will serve as a trigger for the next stage. Before the same, it is therefore appropriate to explain how the Gauss-Seidel algorithm works in general.

As said, the total capacity of the roundabout represents the limited ability of the roundabout itself to dispose of traffic when there are queues at each of the arms.

It is not possible to obtain the total capacity by simply calculating and adding the various entry capacities from the origin/destination $M_{O/D}$ matrix, because in this way the hypothesis of simultaneity would be lost. For the purposes of the calculation, we want to determine the overall capacity $C_T = \sum_{i=1}^{n} C_{ei}^T$ in the hypothesis of simultaneous achievement of the capacity of the single entrances C_{ei}.

This implies the solution of a system of as many equations and equal unknowns, the C_{ei}, as there are afferent arms, which are obtained from the functional relationship incoming capacity/incoming flows $C_{ei} = f_i(Q_{Ci})$ written for each item and imposing the condition $Q_e = C_{ei}$.

The following system of *Equations 13–15* can therefore be written under the hypothesis that there are 3 arms of the roundabout and that no one enters and leaves the same arm, in fact, C_{ei} is not given as a function of itself:

$$C_{e1} = f_1(Q_{C1}) = g_1(C_{e2}, C_{e3}) \tag{13}$$

$$C_{e2} = f_2(Q_{C2}) = g_2(C_{e1}, C_{e3}) \tag{14}$$

$$C_{e3} = f_3(Q_{C3}) = g_3(C_{e1}, C_{e2}) \tag{15}$$

The capacity values of the individual entries are used as starting values $C_{ei} = f_i(Q_C, Q_g)$. To solve this system, the Gauss-Seidel algorithm is used. The method is iterative and, having assigned a set of starting values C_{ei}^1 to the first step, at each step k generates the values C_{e1}^{k+1} for the next step in *Equations 16–18.*

$$C_{e1}^{k+1} = g_1(C_{e2}^k, C_{e3}^k) \tag{16}$$

$$C_{e2}^{k+1} = g_2(C_{e1}^{k+1}, C_{e3}^k) \tag{17}$$

$$C_{e3}^{k+1} = g_3(C_{e1}^{k+1}, C_{e2}^{k+1}) \tag{18}$$

The iterative procedure stops when the convergence test is satisfied, i.e. when the average approximation between two successive solutions becomes less than a value ε = 0.01 ÷ 0.02 considered sufficiently small, i.e. when the relation is verified in *Equation 19*:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{|C_{ei}^{k+1} - C_{ei}^k|}{C_{ei}^k} \leq \varepsilon \tag{19}$$

where n is the number of branches examined. Finally, the total capacity C_T is obtained by adding up all the input capacities for the n branches, determined as follows in *Equation 20*:

$$C_T = \sum_{i=1}^{n} C_{ei}^T \tag{20}$$

In the case study of the present research, it is important to calculate the C_{ei}^T which, added together, gives the total capacity C_T. From now on they will be called $C_{ei}*$ and they will be the ones who will trigger the Gauss-Seidel algorithm in the following stages.

Stage 2

In the second phase, the TRRL model is applied by calculating the Q_{MAX} for the 3 weaving sections of the roundabout (remember that there are 3 sections only because the example is described for a three-branch rotary). *Equations 21–23* deriving from *Equation 1* and specified for the 3 weaving sections 1-2, 2-3, 3-1 are the following:

$$Q_{MAX_{1-2}} = \frac{A \cdot w_{1-2} \cdot \left(1 + {}^{m_{1-2}}/_{w_{1-2}}\right) \cdot \left(1 - {}^{P_{1-2}}/_{3}\right)}{\left(1 + {}^{w_{1-2}}/_{L_{1-2}}\right)} \tag{21}$$

$$Q_{MAX_{2-3}} = \frac{A \cdot w_{2-3} \cdot \left(1 + {}^{m_{2-3}}/_{w_{2-3}}\right) \cdot \left(1 - {}^{P_{2-3}}/_{3}\right)}{\left(1 + {}^{w_{2-3}}/_{L_{2-3}}\right)} \tag{22}$$

$$Q_{MAX_{3-1}} = \frac{A \cdot w_{3-1} \cdot \left(1 + {}^{m_{3-1}}/_{w_{3-1}}\right) \cdot \left(1 - {}^{P_{3-1}}/_{3}\right)}{\left(1 + {}^{w_{3-1}}/_{L_{3-1}}\right)} \tag{23}$$

The crucial parameters are P_i which have the following *Equations 24–26*:

$$P_{1-2} = \frac{Q_{w_{1-2}}}{Q_{T_{1-2}}} = \frac{(b+c)_{1-2}}{(a+b+c+d)_{1-2}} \tag{24}$$

$$P_{2-3} = \frac{Q_{w_{2-3}}}{Q_{T_{2-3}}} = \frac{(b+c)_{2-3}}{(a+b+c+d)_{2-3}} \tag{25}$$

$$P_{3-1} = \frac{Q_{w_{3-1}}}{Q_{T_{3-1}}} = \frac{(b+c)_{3-1}}{(a+b+c+d)_{3-1}} \tag{26}$$

The parameters a, b, c and d which are normally the values associated with the respective traffic flows in the weaving section according to the scheme established in *Figure 1*, in this case, will be a function of the C_{e1}^*, C_{e2}^* and C_{e3}^*.

In order to be expressed as a function of the C_e^*; the α_{ij} percentages matrix has been used; that is, a matrix deriving from the $M_{O/D}$ matrix which explains the proportion of the incoming flow from entry *i*, which is directed towards the exit j. Still in the case of the rotary with 3 branches, if we consider the weaving section 1-2 as an example, the values of a, b, c and d will therefore be expressed as follows (referring to *Figure 1*):

$$a_{1-2} = C_{e1}^* \cdot \alpha_{1-2} \tag{27}$$

$$b_{1-2} = C_{e1}^* \cdot (\alpha_{3-1} + \alpha_{1-1}) \tag{28}$$

$$c_{1-2} = C_{e2}^* \cdot \alpha_{2-2} + C_{e3}^* \cdot \alpha_{2-3} \tag{29}$$

$$d_{1-2} = C_{e3}^* \cdot \alpha_{3-3} \tag{30}$$

Stage 3

Substituting the *Equations 27–30* and their related equivalents for the other two weaving sections 2-3 and 3-1, in *Equations 24–26*, which are then substituted for *Equations 21–23*. All these quoted equations belong to the TRRL model, and they lead to a linear system of n equations and n unknowns, where n is the number of branches.

Such a linear system can be solved again by applying the Gauss-Seidel iterative algorithm, as above described. The C_e^*, descending from *Stage 1* and therefore embedding the HCM-7th model, are then used as the starting solution of the iterations. The final result is $C_{ei}^{\wedge}$ corresponding to the rotary entries capacity array.

4. ROTARY'S RELEVANT INSTANCES

At this point, before concluding this paper, it is appropriate to list some of rotary's relevant instances that have been selected in Italy and the United States.

This step aims to highlight the real-world applicability of the research by analysing and comparing significant geometric configurations of rotaries in both countries to underline the necessity of comprehensive studies on intersection performance. In detail, the authors identified 20 large rotaries, 10 in Italy and 10 in the US.

Rotaries belonging to each group can be classified by geometrical patterns and location (general urban or rural + geographical coordinates).

This classification enables better identification of patterns and potential insights into differences influenced by geography, urbanisation and design norms. As shown in *Figure 2*, measures of interest/affecting capacity were obtained for each rotary, including:

— overall diameter, 2d = D (or D1 and D2 if not circular);
— approach half-widths, vi;
— entry widths, ei;
— effective length of flare, Li;
— entry radii, ri;
— entry angle, Φi.

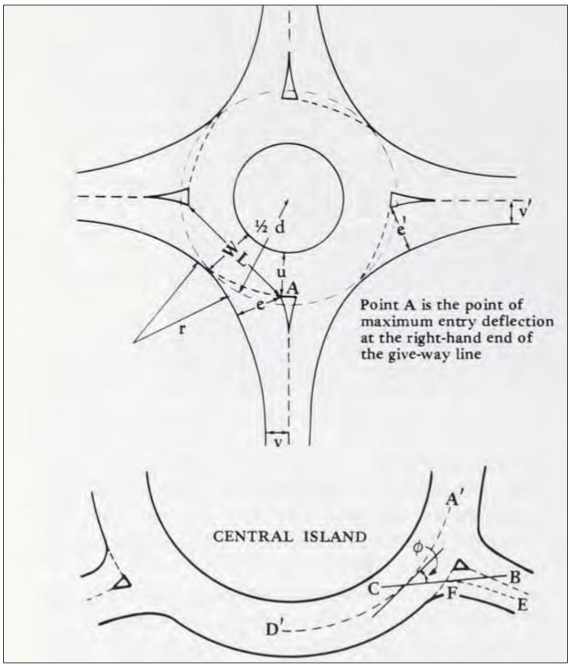

Figure 2 – Key geometric parameters affecting roundabout capacity [17]

The selected circular Italian rotaries range in diameter, D, from 228 to 564 feet (69 to 172 metres) with an average of 343 feet (105 metres). For non-circular roundabouts, D_1 ranges from 570 to 616 feet (174 to 188 metres) with an average of 593 feet (181 metres) and D_2 ranges from 163 to 283 feet (50 to 89 metres) with an average of 223 feet (68 metres). Approach half-widths, v_i, range from 9 to 30 feet (2.7 to 9.1 metres) with an average of 16.3 feet (5.0 metres). Entry widths, e_i, range from 13 to 31 feet (4.0 to 9.4 metres) with an average of 19.5 feet (5.9 metres).

The effective length of flair, L_i, range from 48 feet (15 metres) to 454 feet (138 metres) with an average of 175 feet (53 metres). Entry radii, r_i, range from 76 feet (23 metres) to infinite (tangent entry) with an average of 198 feet (60 metres) for non-tangent approaches. Entry angles, Φ_i, range from zero to 70 degrees with an average of 42 degrees. The selected circular US rotaries range in diameter, D, from 309 to 882 feet (94 to 269 metres) with an average of 528 feet (161 metres). Approach half-widths, v_i, range from 14 to 28 feet (4.3 to 8.5 metres) with an average of 25 feet (7.6 metres). Entry widths, ei, range from 14 to 31 feet (4.3 to 9.4 metres) with an average of 23 feet (7.0 metres). Effective lengths of flair, L_i, range from 50 feet (15 metres) to 964 feet (294 metres) with an average of 239 feet (73 metres). Entry radii, r_i, range from 327 feet (100 metres) to infinite (tangent entry) with an average of 366 feet (112 metres) for non-tangent approaches. Entry angles, Φ_i, range from 20 to 53 degrees with an average of 37 degrees.

Below are therefore some significant examples, 2 Italian and 2 American, extracted from Google Earth Pro, of the rotaries studied (*Figures 3–6* and *Tables 2–5*).

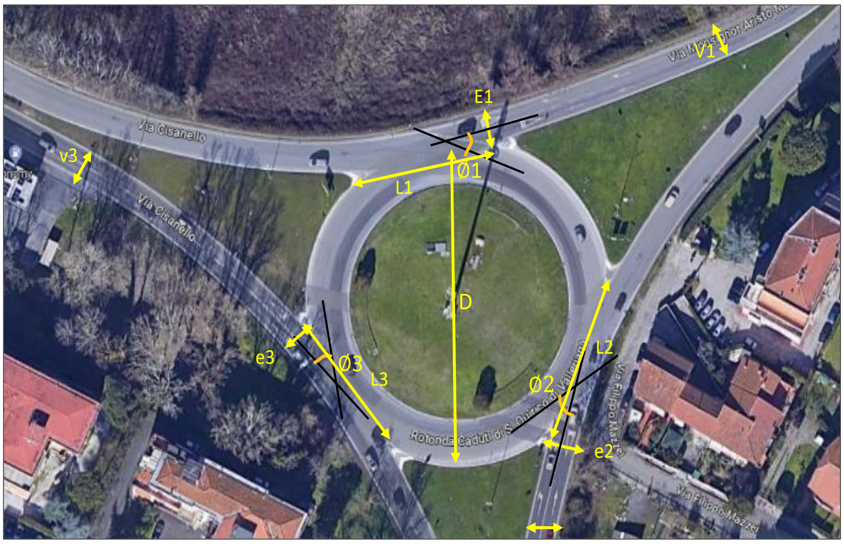

Figure 3 – Rotary 1 (Italy) extracted from Google Earth Pro

Table 2 – Measures of interest of Rotary 1 (Italy)

D = 74 m			43° 42' 24.26" N 10° 26' 07.81" E		
Approach	**v (m)**	**e (m)**	**L (m)**	**r (m)**	**Φ (°)**
1	7	7	28	154	37
2	7	7	30	132	40
3	6	7	27	132	33

Rotary PISA (Tuscany, Italy): Via Cisanello, Via Aristo Manghi

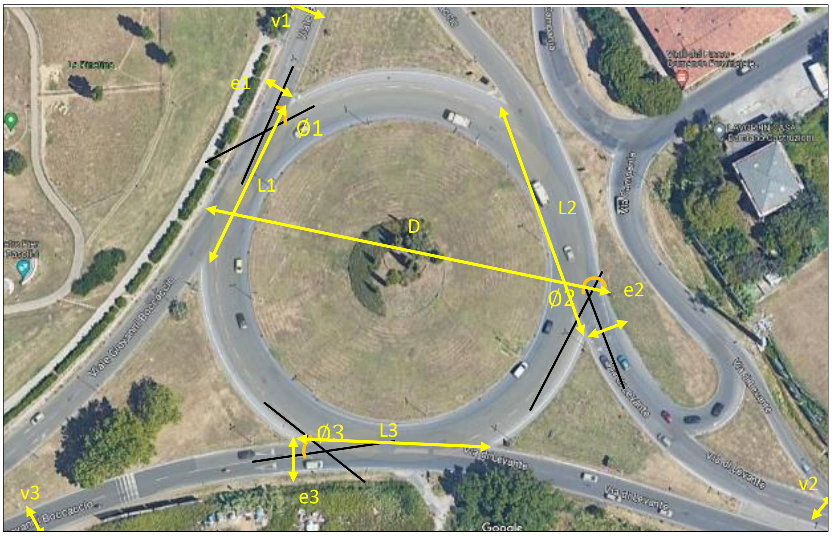

Figure 4 – Rotary 2 (Italy) extracted from Google Earth Pro

Table 3 – Measures of interest of Rotary 2 (Italy)

D = 109 m			43° 32’ 01.77” N 10° 19’ 25.85” E		
Approach	**v (m)**	**e (m)**	**L (m)**	**r (m)**	**Φ (°)**
1	6	7	49	129	39
2	7	10	60	68	49
3	7	8	48	153	45

Rotary LIVORNO (Tuscany, Italy): Via di Levante, Via Boccaccio

Figure 5 – Rotary 3 (US) extracted from Google Earth Pro

Table 4 – Measures of interest of Rotary 3 (US)

D = 267 m			42° 25' 48.40" N 71° 01' 02.03" W		
Approach	**v (m)**	**e (m)**	**L (m)**	**r (m)**	**Φ (°)**
1	13	8	147	144	30
2	7	9	294	127	20
3	15	9	71	N/A	20
4	8	7	60	127	30

Rotary REVERE (Massachusetts, US): Route 60

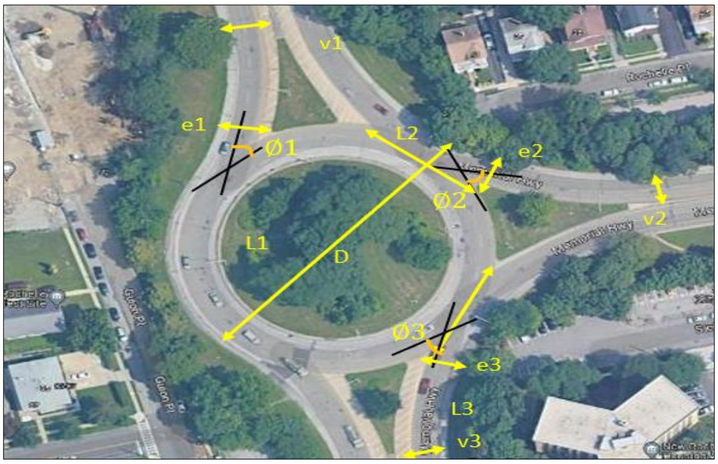

Figure 6 – Rotary 4 (US) extracted from Google Earth Pro

Table 5 – Measures of interest of Rotary 4 (US)

D = 94 m			43° 42’ 24.26” N 10° 26’ 07.81” E		
Approach	**v (m)**	**e (m)**	**L (m)**	**r (m)**	**Φ (°)**
1	7	7	98	100	40
2	7	9	37	100	53
3	8	8	34	100	50

Rotary NEW ROCHELLE (New York, US): Memorial Highway

In conclusion, this section underscores the importance of understanding rotary geometries in different regional contexts and strengthens the research’s argument for developing enhanced capacity models that account for both design variation and geographic location.

5. CONCLUSIONS

Rotaries, also known as traffic circle intersections, are a type of unconventional roundabout where vehicles entering from branches give priority to circulating flow. The existing rotary capacity models only calculate the capacity of individual weaving sections and do not allow for determining the overall performance characteristics of the intersection. Hence, this paper shows how it is possible to derive an entry capacity model for old rotary intersections. In detail, this research regards the combination of two different capacity models, under the condition of total capacity, in a procedure composed of three stages. One of the most relevant aspects of this finding is that in this way it is possible to derive the performance indexes of the rotaries.

This last aspect is generally important on the current practical ground because, even in recent years, the old rotaries continue to be designed and built in several countries. At the same time, there are also severe instances, both in Europe and in the United States, where the appraisal of the performance indexes is crucial for the project to convert an old existing rotary into a better and safer modern roundabout. This step aims to highlight the real-world applicability of the research by analysing and comparing significant geometric configurations of rotaries in both countries to underline the necessity of comprehensive studies on intersection performance.

The analysis underlines that understanding variations in design characteristics, such as entry widths, central island diameters and weaving section lengths, plays a crucial role in identifying the parameters that most significantly impact traffic flow efficiency. In line with this, in the final section of the paper, these practical findings are also highlighted by a brief review of rotary instances collected both in the US and in Europe. To summarise and conclude, the proposed model allows for the calculation of the entry capacity and the consequence LoS for rotary intersections, which cannot be achieved using existing models.

By utilising a mixed method approach and an iteration-based algorithm, i.e. the Gauss-Seidel algorithm, the research provides a more comprehensive evaluation of the performance characteristics of rotary intersections.

The findings of this research contribute to the field by demonstrating the importance of incorporating different methods into a single model and provide a basis for further research and developments in the field of rotary intersection capacity modelling.

The continuation of this research is essential to further validate the proposed model and confirm its real-world applicability. Hence, the next logical step involves applying the model to real-world rotary intersections to verify its robustness and accuracy across different contexts. By conducting case studies and field tests, it will be possible to assess the model’s predictive performance under varying traffic conditions and geometric layouts. Additionally, the insights gained from real-world applications could guide refinements to the model, contributing to the development of design guidelines for both existing and future rotary intersections. This step will not only strengthen the theoretical framework but also bridge the gap between research and practical implementation, enhancing the overall safety and efficiency of traffic flow at these intersections.

ACKNOWLEDGEMENTS

This research work was developed under the project "Smart and Sustainable Use Phase of Existing Roads (S-Super)"; the project has been funded by the University of Pisa annual research program under grant agreement code N° PRA_2020_28.

REFERENCES

[1] Waddell E. Evolution of Roundabout Technology: A History-Based Literature Review. *Computer Science*. 1997.

[2] Jimoh YA, Itiola IO, Adeleke OO. Traffic performance analysis and cost comparison of data collection methods for an urban rotary. *International Journal of Traffic and Transportation Engineering*. 2014;3(5):222-231. DOI: 10.5923/j.ijtte.20140305.03.

[3] Ashford R, Field JC. The capacity of rotary intersections. *Journal of Institution of Highway Engineers*. 1973;20(3):14-21.

[4] Pratelli A, Sechi P, Souleyrette RR. Upgrading traffic circles to modern roundabouts to improve safety and efficiency – case studies from Italy. *Promet – Traffic&Transportation*. 2018;30(2):217-229. DOI: 10.7307/ptt.v30i2.2571.

[5] Italian Ministry of Infrastructures & Transport. *[Norme funzionali e geometriche per la costruzione delle intersezioni stradali]*. D.M. n. 1699 of 10/4/2006, Rome, 2006.

[6] USAID. *Conducting Mixed-Method Evaluations*. Technical Note, Version 1, 2013.

[7] Wu N, Brilon W. Total capacity of roundabouts analyzed by a conflict technique. *Transportation Research Record*. 2018;2672(15):9-22. DOI: 10.1177/0361198118788171.

[8] Almeida F. Strategies to perform a mixed methods study. *European Journal of Education Studies*. 2018;5(1):137-151. DOI: 10.5281/zenodo.1406214.

[9] ITE. *Transportation and Traffic Engineering Handbook*. W.S. Homburger (ed.), Prentice-Hall, New Jersey, 1982.

[10] Ahmad A, Mahesh S, Rastogi R. Selection of roundabout entry capacity model for Indian condition. *Urban Transport Journal*. 2014;13(1):79-87.

[11] TRB. *Highway capacity manual 7th edition: A guide for multimodal mobility analysis*. Washington, D.C.: The National, 2022. DOI: 10.17226/26432.

[12] FHWA. *Highway capacity manual reference guide*. U.S. Department of Transportation, 2022.

[13] Pratelli A, Brocchini L, Francesconi N. Estimating and updating gap acceptance parameters for HCM6th roundabout capacity model applications. *WIT Transactions on Ecology and the Environment*. 2021;253:477-486. DOI: 10.2495/SC210391.

[14] Pratelli A, Souleyrette RR, Brocchini L. Two-geometry roundabouts: Design principles. *Transportation Research Procedia*. 2022;64:299-307. DOI: 10.1016/j.trpro.2022.09.034.

[15] Pratelli A, Brocchini L. Two-geometry roundabouts: Estimation of capacity. *Transportation Research Procedia*. 2022;64:232-239. DOI: 10.1016/j.trpro.2022.09.028.

[16] Kimber RM. The traffic capacity of roundabouts. *TRRL LR942 Monograph*. 1980.

[17] Troutbeck RJ. Capacity and delays at roundabouts - A literature review. *Transportation Research Board*. 1985.

Antonio Pratelli, Lorenzo Brocchini, Reginald Roy Souleyrette, Teng Wang

Un Approccio Misto per la Modellazione della Capacità di Ingresso nelle Vecchie Intersezioni a Rotatoria

Sommario

Le vecchie intersezioni a rotatoria, note anche come grandi rotatorie tradizionali, richiedono ai veicoli in ingresso dalle diramazioni di dare la precedenza al traffico circolante. Una volta immessi, i veicoli percorrono l'isola centrale prima di dirigersi verso la destinazione desiderata, generando conflitti di confluenza e deflessione nei punti di ingresso e di uscita. I modelli di capacità per queste intersezioni si concentrano sulle manovre di intreccio lungo la carreggiata circolare, associando la capacità al flusso massimo di traffico nei segmenti di intreccio. Questo studio propone un nuovo approccio che combina i modelli di capacità delle moderne rotatorie con quelli delle vecchie intersezioni a rotatoria. In particolare, viene sviluppato un metodo misto basato su un processo iterativo che integra il modello inglese

TRRL, progettato per le vecchie intersezioni a rotatoria e basato sulla capacità delle brevi sezioni di intreccio, con le caratteristiche del modello di capacità di ingresso dell'HCM-7th per le moderne rotatorie, che adotta la regola di priorità del traffico circolante. L'approccio presentato si fonda sul concetto di capacità totale, ovvero la condizione in cui tutti gli accessi della rotatoria raggiungono simultaneamente la congestione. Rispetto al passato, questa nuova metodologia consente una stima più accurata delle prestazioni dei rami di ingresso, come il ritardo medio e la lunghezza della coda, colmando il divario tra le metodologie obsolete e quelle attuali nella progettazione e valutazione delle vecchie intersezioni a rotatoria.

Parole Chiave
Modello TRRL di capacità delle rotatorie; Modello HCM delle rotatorie; Capacità totale delle rotatorie; Approccio iterativo combinato; Capacità e prestazioni delle vecchie intersezioni a rotatoria.