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A Mixed Method Approach for Modeling Entry Capacity at Rotary Intersections

A. Pratelli, L. Brocchini, R. R. Souleyrette

Abstract—A rotary is a traffic circle intersection where vehicles entering from branches give priority to circulating flow. Vehicles entering the intersection from converging roads move around the central island and weave out of the circle into their desired exiting branch. This creates merging and diverging conflicts among any entry and its successive exit, i.e., a section. 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. Nevertheless, the single-section capacity value does not lead to the typical performance characteristics of the intersection, such as the entry average delay which is directly linked to its level of service. From another point of view, modern roundabout capacity models are based on the limitation of the flow entering from the single entrance due to the amount of flow circulating in front of the entrance itself. Modern roundabouts capacity models generally lead also to a performance evaluation. This paper aims to incorporate a modern roundabout capacity model into an old rotary capacity method to obtain from the latter the single input capacity and ultimately achieve the related performance indicators. Put simply; the main objective is to calculate the average delay of each single roundabout entrance to apply the most common Highway Capacity Manual, or HCM, criteria. The paper is organized as follows: firstly, the rotary and roundabout capacity models are sketched, and it has made a brief introduction to the model combination technique with some practical instances. The successive section is deserved to summarize the TRRL old rotary capacity model and the most recent HCM-7th modern roundabout capacity model. Then, the two models are combined through an iteration-based algorithm, especially set-up and linked to the concept of roundabout total capacity, i.e., the value reached due to a traffic flow pattern leading to the simultaneous congestion of all roundabout entrances. The solution is the average delay for each entrance of the rotary, by which is estimated its respective level of service. In view of further experimental applications, at this research stage, a collection of existing rotary intersections operating with the priority-to-circle rule has already started, both in the US and in Italy. The rotaries have been selected by direct inspection of aerial photos through a map viewer, namely Google Earth. Each instance has been recorded by location, general urban or rural, and its main geometrical patterns. Finally, conclusion remarks are drawn, and a discussion on some further research developments has opened.

Keywords— Mixed methods, old rotary and modern roundabout capacity models, total capacity algorithm, level of service estimation.

I. INTRODUCTION

ROTARY intersections are classified as a special type of unconventional roundabouts and often they are also called

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old traffic circles or old rotaries. These last names belong to the matter that in the early '60s the first roundabouts were conceived on the yield-at-entry rule. After World War II, vehicles and highways grew up fast and rotary technology was mainly developed in the United Kingdom. British researchers experimentally saw that rotary intersections were safer than crossroads [1]. Nevertheless, such a "priority-to-branch" rule generally works well at any cross intersection, but it is not well-suited for the entries of a traffic circle, where it gave the right of way to vehicles entering the circle. 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 meters 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. As a consequence, the value of the maximum rate of flow is therefore precisely linked to the weaving sections of the rotary, which means that therefore the rotary capacity models are based on such weaving maneuvers in the sections of the rotary itself. Starting from these considerations, at the beginning of the 1950s, the Transport and Road Research Laboratory developed a research project base 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 very 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-to-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, priority-to-circle modern roundabouts have become increasingly common, and a large amount of experimental performance data has become available on any single 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 today often designed, and built in some world countries applying the TRRL model without any possibilities of performance evaluation. In addition, there exist instances where the intersections National guidelines ask for a short weaving section approach for modern roundabouts with very large diameters. 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 meters. 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. Secondly, 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. At the end and before conclusions, a chapter has been added relating to some

rotary's relevant instances from Italy and America.

II. METHODOLOGY

A. 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, there are 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.

B. 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 utilization for 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 meters i.e., about 150 ft. For this last reason, roundabouts exceeding such threshold are classified as "unconventional" and they must have 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 then 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 and which are precisely considered as short sections of exchange. The TRRL formula is the following (1):

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

The formula above calculates the value of the maximum hourly flow rate Q_{MAX} that can be used in an interchange section and which, using the constant $A = 354$, is a function of various parameters. In detail: the average width m in meters at the start of the change section, the length L in meters of the section and the proportional incidence P of the interweaving current $Q_w = (b + c)$ on the total traffic flow $Q_T = (a + b + c + d)$ in the section itself. Expression (1) overestimates the flow rate for small and compact roundabouts (when the flow rate value is lower than 4000 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 expression (2):

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

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 Fig. 1.

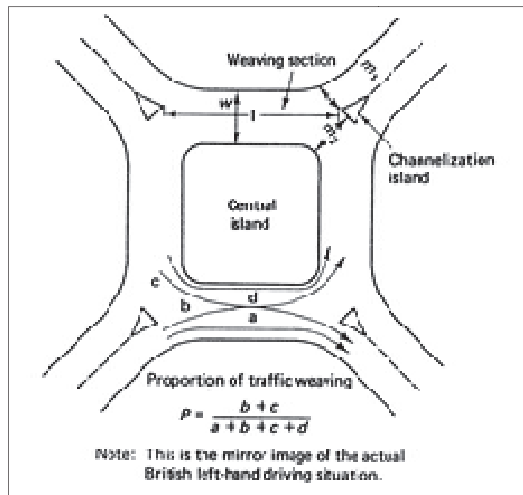


Fig. 1 Scheme of method of the TRRL - Transport Road Research Laboratory, also known as “English Method” [9]

The values obtained from the expression (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 (3)

must be satisfied each time for each exchange section:

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

C. 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 characterized 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 (4):

$$C_e = A e^{(-BQ_c)} \quad (4)$$

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 t_c (default or local calibration);
- progress follow-up value t_f (default or local calibration).

Once the entry capacity of the analyzed 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 maneuver, urban and rural and recreational location. The level of service is referred to a scale 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 directly 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 the expression (5):

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

where:

- C is entry capacity (vehicles/h);
- x is Q/C ratio;
- T is 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 I:

TABLE I
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

D. 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 calculate 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 meters 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 two 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 themselves by the fact each one can be referred to a common resulting effect, i.e., the rotary total capacity [7]. The total capacity of a traffic circle is defined in respect to 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 traffic circle 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 evidences: 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.

III. 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 (6), (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:

$$E[w]_i = \frac{2000 + c_i}{c_{ei} - Q_{ei}} \quad (6)$$

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

More in general, the previous expression (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. Expression (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 expression (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 by 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), (9), (10), (11) and (12) the weaving sections considered are n and the generic texture section is i, i+1.

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

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

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

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

then, consequently:

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

and finally:

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

leading to a system of linear equations, one for every of the n sections forming the rotary. The unknowns of this system of n linear equations that brings 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 safe of simplicity, the algorithm application is described though the instance of a three-branch rotary as it 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 $C_{e_1}^*$, $C_{e_2}^*$ and $C_{e_3}^*$ 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 capacity 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 $C_T = \sum C_{e_i}$ in the hypothesis of simultaneous achievement of the capacity of the single entrances C_{e_i} .

This implies the solution of a system of as many equations

and equal unknowns, the C_{e_i} , as there are afferent arms, which are obtained from the functional relationship incoming capacity/incoming flows $C_{e_i} = f_i(Q_c)$ written for each item and imposing the condition $Q_e = C_{e_i}$. The following system of Equation (13), Equation (14) and Equation (15) can therefore be written under the hypothesis that there are three arms of the roundabout and that no one enters and leaves the same arm, in fact, C_{e_i} is not given as a function of itself:

$$C_{e_1} = f_1(Q_{C1}) = g_1(C_{e_2}, C_{e_3}) \quad (13)$$

$$C_{e_2} = f_2(Q_{C2}) = g_2(C_{e_1}, C_{e_3}) \quad (14)$$

$$C_{e_3} = f_3(Q_{C3}) = g_3(C_{e_1}, C_{e_2}) \quad (15)$$

The capacity values of the individual entries are used as starting values $C_{e_i} = f_i(Q_c, Q_g)$. To solve this system, the Gauss-Seidel algorithm is used. The method is iterative and, having assigned a set of starting values $C_{e_i}^1$ to the first step, at each step k generates the values $C_{e_i}^{k+1}$ for the next step (16), (17) and (18):

$$C_{e_1}^{k+1} = g_1(C_{e_2}^k, C_{e_3}^k) \quad (16)$$

$$C_{e_2}^{k+1} = g_2(C_{e_1}^{k+1}, C_{e_3}^k) \quad (17)$$

$$C_{e_3}^{k+1} = g_3(C_{e_1}^{k+1}, C_{e_2}^{k+1}) \quad (18)$$

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 $\varepsilon = 0.01 \div 0.02$ considered sufficiently small, i.e., when relation (19) is verified:

$$\frac{1}{n} \sum_{i=1}^n \frac{|C_{e_i}^{k+1} - C_{e_i}^k|}{C_{e_i}^k} \leq \varepsilon \quad (19)$$

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 (20):

$$C_T = \sum_{i=1}^n C_{e_i}^T \quad (20)$$

In the case study of the present research, it is important to calculate the $C^T_{e_i}$ which, added together, give the total capacity C_T . From now on they will be called $C_{e_i}^*$ 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 (1) is applied by calculating the Q_{MAX} for the three weaving sections of the roundabout (remember that there are three sections only because the example is described for a 3-branch rotary). The three equations deriving from (1) and specified for the three weaving sections 1-2, 2-3, 3-1 are the following:

$$Q_{MAX_{1-2}} = \frac{A \cdot w_{1-2} \cdot (1 + m_{1-2} / w_{1-2}) \cdot (1 - P_{1-2} / 3)}{(1 + w_{1-2} / L_{1-2})} \quad (21)$$

$$Q_{MAX_{2-3}} = \frac{A \cdot w_{2-3} \cdot (1 + m_{2-3}/w_{2-3}) \cdot (1 - P_{2-3}/3)}{(1 + w_{2-3}/L_{2-3})} \quad (22)$$

$$Q_{MAX_{3-1}} = \frac{A \cdot w_{3-1} \cdot (1 + m_{3-1}/w_{3-1}) \cdot (1 - P_{3-1}/3)}{(1 + w_{3-1}/L_{3-1})} \quad (23)$$

The crucial parameters are P_i which have the following expression:

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

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

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

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 Fig. 1, in this case will be a function of the $C_{e_1}^*$, $C_{e_2}^*$ and $C_{e_3}^*$. In order to be expressed as a function of the $C_{e_i}^*$ 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 three 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 Fig. 1):

$$a_{1-2} = C_{e_1}^* \cdot \alpha_{1-2} \quad (27)$$

$$b_{1-2} = C_{e_1}^* \cdot (\alpha_{3-1} + \alpha_{1-1}) \quad (28)$$

$$c_{1-2} = C_{e_2}^* \cdot \alpha_{2-2} + C_{e_3}^* \cdot \alpha_{2-3} \quad (29)$$

$$d_{1-2} = C_{e_3}^* \cdot \alpha_{3-3} \quad (30)$$

Stage 3. Substituting Equation (27), Equation (28), Equation (29) and Equation (30) and their related equivalents for the other two weaving sections 2-3 and 3-1, in Equation (24), Equation (25) and Equation (26), which are then substituted for Equation (21), Equation (22) and Equation (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 linear system can be solved again applying the Gauss-Seidel iterative algorithm, as above described. The $C_{e_i}^*$, descending from *Stage 1* and therefore embedding the HCM-7th model, are then used as starting solution of the iterations. The final result is $C_{e_i}^{\wedge}$ corresponding to the rotary entries capacity array.

IV. 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. In detail, the authors identified 20 large rotaries, 10 in Italy and 10 in the USA. Rotaries belonging to each group can be classified by geometrical patterns and location (general urban or rural +

geographical coordinates). As shown in Fig. 2, Measures of interest capacity were obtained for each rotary, including:

- Overall diameter, $2d = D$ (or D_1 and D_2 if not circular);
- Approach half-widths, v_i ;
- Entry widths, e_i ;
- Effective length of flare, L_i ;
- Entry radii, r_i ;
- Entry angle, Φ_i .

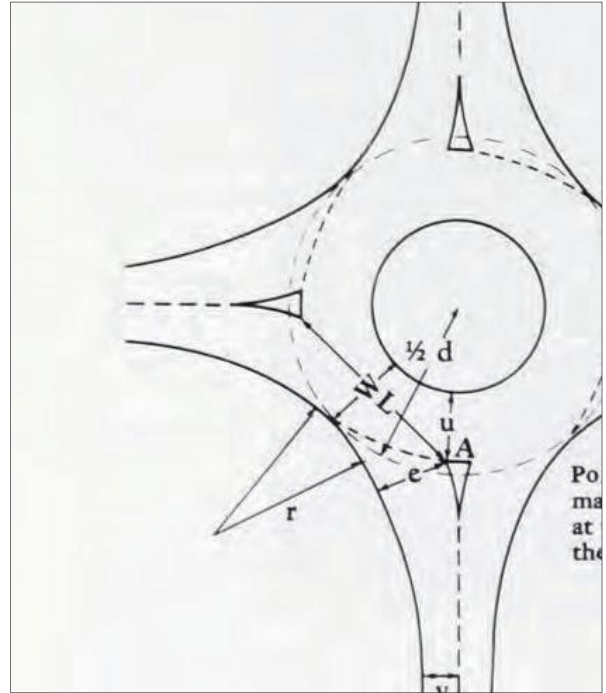


Fig. 2 Image showing measures of interest/affecting [17]

The selected circular Italian rotaries range in diameter, D , from 228 to 564 feet (69 to 172 meters) with an average of 343 feet (105 meters). For non-circular roundabouts, D_1 ranges from 570 to 616 feet (174 to 188 meters) with an average of 593 feet (181 meters) and D_2 ranges from 163 to 283 feet (50 to 89 meters) with an average of 223 feet (68 meters). Approach half-widths, v_i , range from 9 to 30 feet (2.7 to 9.1 meters) with an average of 16.3 feet (5.0 meters). Entry widths, e_i , range from 13 to 31 feet (4.0 to 9.4 meters) with an average of 19.5 feet (5.9 meters). The effective length of flair, L_i , range from 48 feet (15 meters) to 454 feet (138 meters) with an average of 175 feet (53 meters). Entry radii, r_i , range from 76 feet (23 meters) to infinite (tangent entry) with an average of 198 feet (60 meters) 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 meters) with an average of 528 feet (161 meters). Approach half-widths, v_i , range from 14 to 28 feet (4.3 to 8.5 meters) with an average of 25 feet (7.6 meters). Entry widths, e_i , range from 14 to 31 feet (4.3 to 9.4 meters) with an average of 23 feet (7.0 meters). Effective lengths of flair, L_i , range from 50 feet (15 meters) to 964 feet (294 meters) with an average of 239 feet (73 meters).

Entry radii, r_i , range from 327 feet (100 meters) to infinite (tangent entry) with an average of 366 feet (112 meters) 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, two Italian and two American, extracted from Google Earth Pro, of the Rotaries studied (Fig. 3 to Fig. 6 and Table II to Table V).

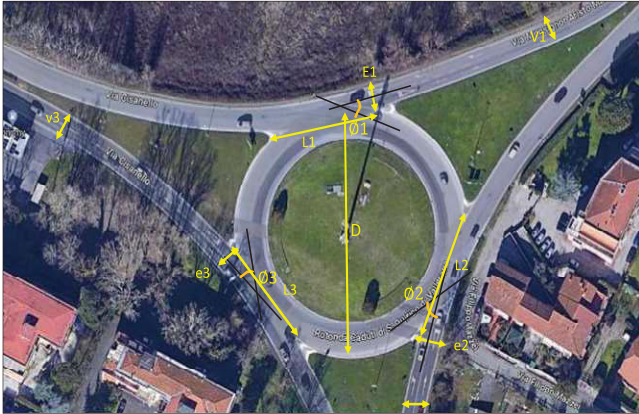


Fig. 3 Rotary 1 (Italy) extracted from Google Earth Pro

TABLE II
MEASURES OF INTEREST OF ROTARY 1 (ITALY)

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

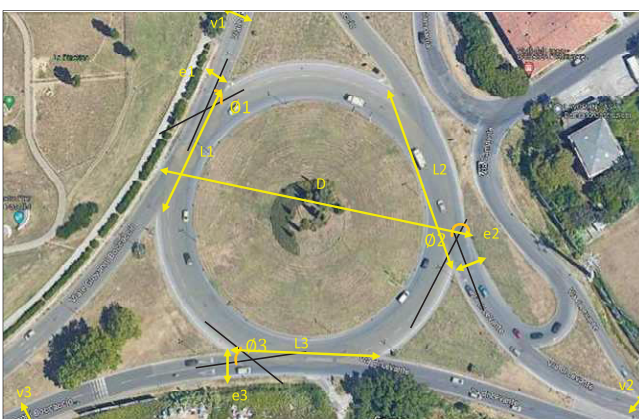


Fig. 4. Rotary 2 (Italy) extracted from Google Earth Pro

TABLE III
MEASURES OF INTEREST OF ROTARY 2 (ITALY)

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



Fig. 5 Rotary 3 (US) extracted from Google Earth Pro

TABLE IV
MEASURES OF INTEREST OF ROTARY 3 (US)

3. Rotary REVERE (Massachusetts, US): Route 60					
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

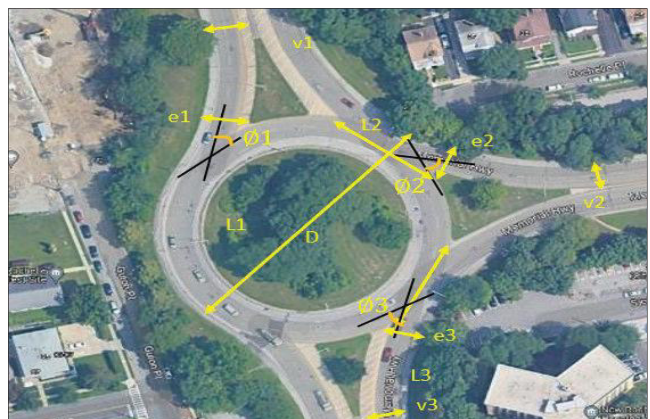


Fig. 6 Rotary 4 (US) extracted from Google Earth Pro

TABLE V
MEASURES OF INTEREST OF ROTARY 4 (US)

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

V. 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 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 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 build 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. About this, in the last part of the present paper, these practical findings are also highlighted by a brief review of rotary instances collected both in the US and in Europe. To simply summarize 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 utilizing 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 modeling.

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