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Two-Geometry Roundabouts: Estimation of Capacity

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Abstract

The authors have already developed and studied the Two-Geometry Roundabouts in terms of design principles. This paper in fact is the natural extension a previous article by Pratelli et al., 2022, in which the authors discussed the main concepts of the Two-Geometry Roundabouts and the details that determine their success. However, when someone talks about roundabouts in general, it is also essential to specify which respective capacity model is most suitable. The Highway Capacity Manual (HCM6th) provides a popular method for estimating the capacity of conventional roundabouts. Nevertheless, the Two-Geometry Roundabouts are classified as unconventional roundabouts, and therefore this paper aims to answer the following crucial question: "*Which capacity model should be used to calculate a Two-Geometry Roundabout?*". Firstly, the impositions of the Italian guidelines, where all roundabouts with a non-circular shape or with an inscribed diameter greater than 50 meters are defined as unconventional, are described. The achieved empirical results in respect to some test has compared with those otherwise obtained through the HCM6th methodology. Next, two popular methods suitable for calculating the capacity of Two-Geometry Roundabouts are resumed, namely the SETRA method and the Brilon-Wu method. These two are chosen because on the one hand SETRA directly requests dimensions of some selected geometric components; while on the other hand, the Brilon-Wu approach is based only on a few macro characteristics such as the number of entry/circulation lanes and the values of the gap acceptance parameters. Then, the successive section is devoted to comparing performance between a Traditional circular Roundabout and a Two-Geometry Roundabout, designed for the same intersection. This comparison was carried out through the use of experimental results obtained with a dynamic simulation approach made with Aimsun software. Finally, the paper ends with a brief discussion on some possible insights framed in a further development of the research, which could involve the safety models of Two-Geometry roundabouts, and their possible extension to roundabout corridors.

Keywords: Unconventional Roundabouts Capacity; Two-Geometry Roundabouts; SETRA method; Brilon-Wu method; Aimsun Simulations.

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1. Introduction of Capacity Models

First of all, it is appropriate to start with a premise: this paper is the natural extension of another article named "Two-Geometry Roundabouts: Design Principles" in which the Authors discussed the main concepts of the Two-Geometry Roundabouts and the details that determine their success. The so-called Two-Geometry Roundabout is an unconventional roundabout with the shape of the outer edge different from that of the central island (usually the outer edge is elliptical and the central island remains circular). This entails a peculiarity of the Two-Geometry Roundabout, namely the fact of having a variable ring width (while in a classic roundabout the ring width is fixed). The main advantages of the Two-Geometry Roundabout are related to its particular geometry, which is effective in deviation of the trajectories and consequently on speeds lowering. Furthermore, during the design phase, they are less bulky than the classic roundabouts and are well suited to be inserted in any strongly constrained context. Finally, thanks to their geometrical enhanced flexibility, which is the ring lane with variable width, they are more easily passable even by large OSOW (OverSized/OverWeight) vehicles. As regards the novelties underlying these studies, the greatest is certainly the research of the most suitable capacity calculation model for Two-Geometry Roundabouts, as there are currently several guidelines but no specific model. Now, it is therefore necessary to remember what is meant by "Roundabout Capacity" and what are the most relevant mathematical models to calculate it. The capacity of a roundabout has defined as the maximum number of vehicles that can enter the roundabout in unit time at a given entry leg for the flow in a circulating roadway. There exist several methods to calculate the capacity of a conventional roundabout entrance. In this research, only a few of them were considered as only some of them can be considered suitable for unconventional roundabouts and in particular for the Two-Geometry Roundabouts. Generally speaking, the roundabout capacity models can be divided into three groups and their features of these are discussed briefly below:

1. Theoretical models, based on "gap-acceptance" theory;
2. Empirical models, obtained by regression on experimental data;
3. Simulation models.

As for the capacity calculation of the Two-Geometry Roundabouts through simulation models, they are part of the possible development of this research, and they have only been quoted in the following sections. Instead, as regards Theoretical models, they have based on the "Gap-acceptance" theory, which has based on the behavioural analysis of drivers entering a major traffic flow from a minor traffic flow (decision level). The key variables here are t_c (critical headway) and t_f (follow-up headway) which are precisely characteristic of drivers. In fact, the Gap acceptance models have been strongly affected both by driver behaviours and local habits. In this way, in the field of Two-Geometry Roundabouts these parameters estimation relayed both on different local studies and experimental calibrations at the regional/national level, are crucial. Therefore, when you make the choice of applying a theoretical model for the capacity calculation of a Two-Geometry Roundabout, according to the specific geographic location, you should use the corresponding local observed/calibrated parameters (if available). The most popular theoretical models are:

- Australian method;
- HCM6th (Highway Capacity Manual, Sixth Edition) method;
- Brilon-Wu method.

Finally, as regards empirical models, the relation between the entry capacity and the circulating flow rate has been estimated from capacity observations. Many empirical models were developing over the years and some of the most popular are:

- Kimber model;
- SETRA (Service d'Ètudes Techniques des Routes et Autoroutes) simplified model;
- Swiss model.

All the methods listed above have been designed and developed for conventional roundabouts. However, in recent years, unconventional roundabouts have been developing more and more, including of course the Two-Geometry Roundabouts. Therefore, this paper aims to answer the question: "*Which capacity model should be used to calculate a Two-Geometry Roundabout?*".

2. Italian legislation vs. HCM6th methodology

After having illustrated the main methods of calculating the roundabout capacity, an example of the calculation of a Two-Geometry Roundabout designed in Tuscany (It.) on an existing intersection on National Highway SS n.73 "Senese-Aretina" has shown below (Fig. 1a). The roundabout planned on SS n. 73 is, as previously said, a Two-Geometry Roundabout (Fig. 1b), a typology that does not fall within those of point 4.5.1 of the Ministerial Decree of 2006 (Functional and geometric standards for the construction of intersections. For this reason, the aforementioned roundabout has been classified as an un-conventional roundabout and must have been calculated with the "principle of exchange sections between two contiguous arms". It is emphasized that for, and only for, the Italian design standards all roundabouts both not circularly shaped and/or with an external diameter D greater than 50 m, i.e., about 150 ft, fall into this category.

a b

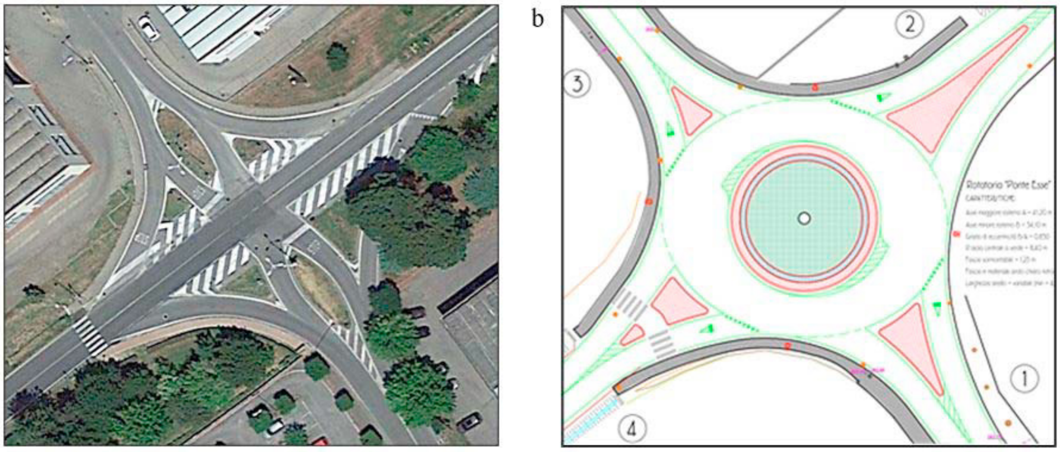

Fig. 1. Esse Bridge intersection on National Highway SS n.73, Arezzo (Tuscany, It.): (a) Aerial view of the present state; (b) Layout of the design solution resolved as a Two-Geometry Roundabout (*sources*: (a) Google Earth Pro™; (b) courtesy by the Authors).

Therefore, the Transport Road Research Laboratory, or TRRL method, also known as the "English Method", has been applied, which consists of a specific calculation method for the sizing and verification of the different individual sections between successive entrances of a roundabout and which are intended as short swap traits. The TRRL formula is the following (1):

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

Then, the procedure goes on to compute the value of the maximum hourly flow rate Q_{MAX} that can be used in an exchange section and which, through the constant $A = 354$, is a function of the average width m in meters at the beginning of the exchange section, of the length L in meters of the section and the proportional incidence P of the interlacing current $Q_I = (b + c)$ on the total traffic flow $Q_T = (a + b + c + d)$ in the section itself (the formula overestimates the capacity for small or compact roundabouts and when in such cases there is a calculated capacity value of less than 4000 vehicles/h, then the calculation must be repeated with a reduced constant $A = 302$). P has defined by the expression (2):

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

With values of a, b, c and d associated with the respective traffic flow in the exchange section according to the scheme established in Fig. 2.

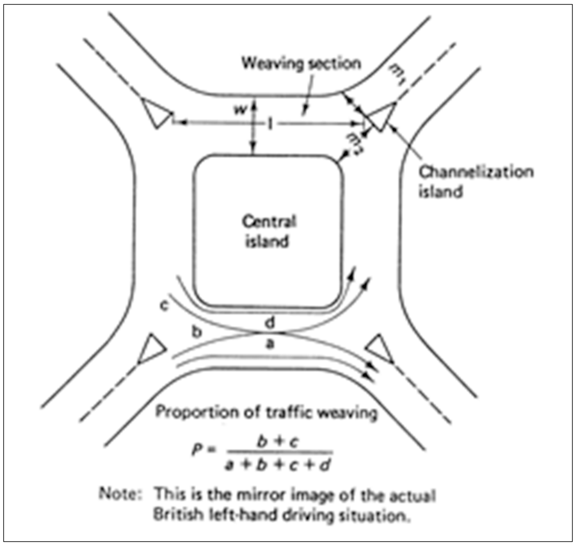

Fig. 2. Scheme of the method of the TRRL - Transport Road Research Laboratory, also known as the "English Method" (*source*: Transportation and Traffic Engineering Handbook, 1982).

The values obtained from the formula are obviously the maximum values of the capacities of the different interchange sections, which correspond, to congestion conditions, with long queues and modest outflow speeds, around 16 km/h. The verification test has been obtained every time for each section of exchange and it results (3):

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

The capacity and performance calculations were repeated by applying the method of the Manual HCM6th, the most used Theoretical model based on the "Gap-acceptance" theory. This has been done because it is clear that it is very unlikely that a stretch of just twenty meters in length can actually be used as a real section of exchange between several vehicles of different traffic currents. In HCM6th, 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. In the Two-Geometry Roundabouts, there are two cases of different combinations because the width of the ring is variable. In particular, there are two lanes in the ring in front of two of the entrances and one lane in the ring in front of the other two. To apply the HCM6th calculation procedure, the values of the critical headway and follow-up headway parameters calibrated for Tuscany had used. The conclusions that can be drawn from the calculation with the HCM6th Method are quite similar to those that have previously been obtained through the English Method, therefore both methods are valid for the Two-Geometry Roundabouts.

3. The German method Brilon-Wu and the French method SETRA

After having reported an example of the calculation, carried out with two comparable methods of a project of a real roundabout, the two methods most used today for the Two-Geometry Roundabouts will be illustrated. It is possible to affirm that the two most currently used methods for estimating the capacity of Two-Geometry Roundabout are: the

German method of Brilon-Wu (in the group of Theoretical models) and the French method of SETRA - Service d'Ètudes Techniques des Routes et Autoroutes (in the group Empirical models).

3.1. Brilon-Wu method

The German method of Brilon-Wu, similar to the Australian one in that it is based on Tanner's idea, was proposed by Brilon-Wu (Brilon et al., 1997) and reports a formula for calculating the capacity then also adopted by the German regulation HBS 2001. In this formulation (4), therefore, the calculation of the capacity C_e is a function of the circulating flow, the number of lanes at the ring and at the entrance branches and also the behaviour of users through the critical headway, the follow-up headway and the distance between the vehicles in circulation.

$$C_e = 3600 \cdot \left(1 - \frac{t_m \cdot Q_c/_{3600}}{n_c}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot exp\left[\frac{-Q_c}{3600 \cdot (t_c - {}^{t_f}/_2 - t_m)}\right] \tag{4}$$

Where:

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

Brilon, in the calibration of the model, estimated: $t_c = 4.1$ seconds, $t_f = 2.9$ seconds and $t_m = 2.1$ seconds. In any case, as has already been said this formula is suitable for the assessment of the capacity of all conventional and unconventional roundabouts including the Two-Geometry Roundabout, provided that calibrated parameters are available for local conditions. For example, in a study conducted in Lucca (Tuscany, It.) in 2020 the estimated parameters were $t_c = 3{,}6$ seconds and $t_f = 2{,}5$ seconds.

3.2. SETRA method

The SETRA method is a French Empirical method from the 1980s by the Service d'Ètudes Techniques des Route et Autoroutes (SETRA), developed on the basis of a survey campaign on 17 suburban roundabouts with a diameter of about 40 meters (In total 56 entrances were analyzed). The geometric quantities used are pointed out in Table 1 while in Fig. 3 a graphic representation together with the flows considered is shown.

Table 1. Geometric quantities and flows considered in the SETRA method.

Acronym	Meaning
ANN	Ring width [m]
ENT	Width of the entrance lane measured about 6 m from the precedence line [m]
SEP	Width of the central reserve island [m]
Qc	Circulating flow [vehicles/h]
Qe	Incoming flow [vehicles/h]
Qu	Outgoing flow [vehicles/h]

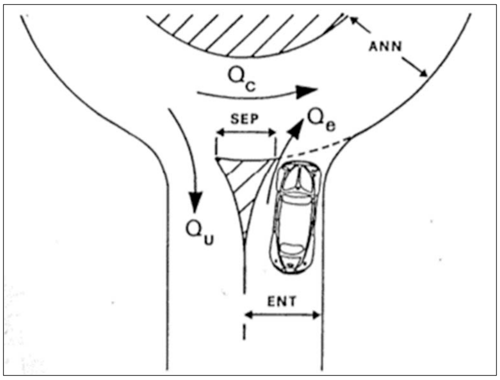

Fig. 3. Geometric quantities and flows considered in the SETRA method (*source*: SETRA, 1984).

The procedure is as follows: the equivalent outgoing flow Q_{u*} is obtained with equation (5); the disturbance flow Q_g is determined with equation (6); the capacity of the entrance C_e is obtained with equation (7).

$$Q_{u*} = Q_u \cdot \frac{15-SEP}{15} \tag{5}$$

$$Q_g = \left(Q_c + {}^2/_3 \cdot Q_{u*}\right) \cdot [1 - 0.085 \cdot (ANN - 8)] \tag{6}$$

$$C_e = \left(1330 - 0.7 \cdot Q_g\right) \cdot [1 + 0.1 \cdot (ENT - 3.5)] \tag{7}$$

The input capacity, therefore, depends on the disturbance flow and the branch width entrance to which 3.5 meters are subtracted (the standard width of a lane). From equation (7) it is clear that with respect to one meter of increase in the width of the entrance branch there is a corresponding increase in 10% of capacity.

The SETRA method gives great relevance to the geometric parameters of the roundabouts. As consequence, this method can also be well-suited for unconventional roundabouts, and in particular for Two-Geometry Roundabouts. For example, when you want to redesign an existing roundabout, or you are designing a new roundabout that involves any decision on geometric characteristics.

4. Possible future development: Simulations with Aimsun software

Before drawing conclusions, possible future research developments have been presented in this section. In particular, a comparison of traffic simulations carried out by Aimsun software between two different types of roundabouts has been described: in respect to the same instance of experimental intersection, a Two-Geometry Roundabout design solution has been compared to a Traditional Roundabout one. The road intersection under study is located between Provincial Highway SP n.1 and Provincial Highway SP n.25 in North Tuscany (It.) At the current state, the node appeared as a level intersection where the four road branches converged, three of which were of considerable importance while the fourth branch was passed by a scarce number of vehicles and was in fact redeveloped as a protected pedestrian path. The two proposed solutions are a Two-Geometry Roundabout (Fig. 4a) and a Traditional Roundabout (Fig. 4b), whose comparison was made using the Aimsun™ software.

a b

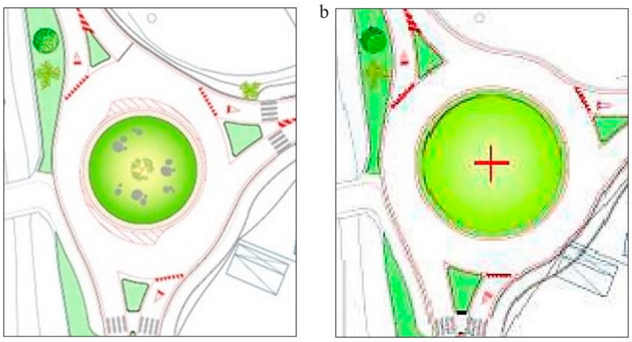

Fig. 4. Experimental sample in Tuscany (It.): (a) Two-Geometry Roundabout; (b) Traditional Roundabout (*sources*: courtesy by the Authors).

Once the input data for the Aimsun software (the roundabout geometry and traffic data) were set, various simulations were performed and among the outputs that the software provides, the delay time was taken into consideration (as it is the most significant parameter for our research). As for the traffic data, different O/D matrices (Origin/Destination matrices) have been recreated starting from a matrix composed of themselves equivalent vehicles only, up to 5 additional scenarios corresponding to the presence of 5%, 10%, 15%, 20% and 25% of heavy vehicles. Below are the results of the entry delay time values extracted from the Aimsun software, reporting them in a graph (Fig. 5) which compares the Two-Geometry Roundabout with the Traditional Roundabout for the 6 scenarios adopted.

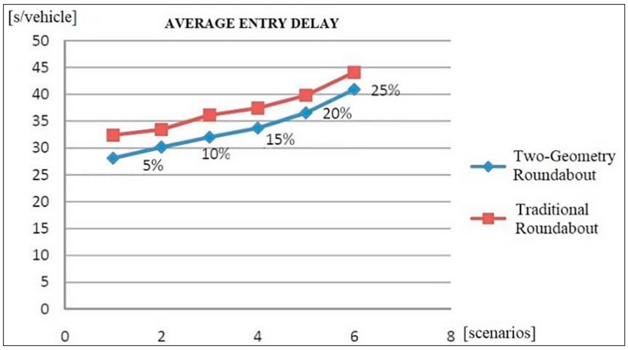

Fig. 5. Comparison between the delay times of Two-Geometry Roundabout and Traditional Roundabout (*source*: courtesy by the Authors).

As it can be easily seen, the graph in Fig. 5 clearly shows that the Two-Geometry Roundabout has lower average entry delay time values than those of the Traditional Roundabout in all the scenarios examined. So, it can be expected a better Level of Service (LoS is a qualitative measure used to relate the quality of motor vehicle traffic service; the HCM defines LoS for signalized and unsignalized intersections as a function of the average vehicle entry delay and it can be included between A, the best LoS and F, the worst LoS). Indeed, the distance between each pair of points belonging to the two different curves is greater than 5 s/vehicle. This last value can be seen as a discriminant of the LoS, since it corresponds to half the 10 s range width of both LoS C and LoS D. Therefore when the average entry delay in a Two-Geometry roundabout is at LoS C or D, but it is close at the upper limit of the respective average delay range, there is a high probability that a Traditional Roundabout solution under the same traffic conditions could instead be at LoS D or E, i.e. with 5 s/vehicle more of average delay. Clearly, it is fair to point out that this is only one of the outputs that a simulation software can provide. Therefore, further studies and comparisons are required in order to select which of the two roundabouts is absolutely the best. However, in conclusion, is it possible to affirm that, even if the capacity of the two possible solutions (Two-Geometry Roundabout and Traditional Roundabout) was not calculated, the simulation models are a powerful tool to compare multiple solutions and, in our case, highlight the positive aspects of Two-Geometry Roundabouts.

5. Conclusions

The Two-Geometry Roundabouts are unconventional roundabouts with the shape of the external margin different from that of the central island (in other words, the circulating roadway width is not constant). In addition, when talking about roundabouts it is of fundamental importance to talk about the evaluation of their capacity. The development of this research started from these two statements, and this paper, served to seek an answer to the question: "*Which capacity model should be used to calculate a Two-Geometry Roundabout?*". After having studied and deepened the different methods existing for calculating the capacity of all several roundabouts, is it possible to affirm that to date there is no univocal answer to this question because each calculation method has strengths and weaknesses. In order to answer such a question would probably require more experimental data. However, there are currently too few Two-Geometry Roundabouts to which the methods described can be applied. Surely this is the main weakness of the research which, however, may be overcome by future investigations; then this paper can be framed as a starting/basic conceptual approach. In any case, it is possible to affirm, without a doubt, that dynamic simulation remains a powerful tool to use, regardless of the type of roundabout being considered. In fact, starting from this, in future developments and in the advancement of this research, the authors will first of all try to give a univocal answer on the estimation of the capacity of the Two-Geometry Roundabouts. Furthermore, always the authors will implement both the studies related to the safety models of roundabouts and the way to apply them to the Two-Geometry Roundabouts and the studies related to the roundabout corridors and the possible introduction in them of the Two-Geometry Roundabouts.

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