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Tools and models for testing the capacity, level of functionality and performances for two-lane roundabout

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Summary

Starting with the first decade of the XXth century, the first signs of interest appear for the arrangement of circular crossroads in America and in Europe as well. A history of the evolution of such types of arrangements is presented up until modern endorsements from our days.

This paper presents a case study for a two-lane roundabout, positioned in the Municipality of Cluj-Napoca, Romania. The capacity of circulation, the level of functionality and the performance of the crossroad are analysed by using the analytical and empirical models.

Moreover, the relationship between entry flow and the circulating flow is analysed, based on the observations made within 15 minutes intervals at the morning and the afternoon peaks of the traffic from the area.

KEYWORDS: roundabout capacity, gap-acceptance theory, empirical theory

1. INTRODUCTION

The concept of the roundabout was introduced both in America and Europe in the early 1900s, being developed over the course of 100 years, many countries and researchers from all over the world contributing to today's degree of knowledge.

The design of these intersections was based initially on heuristic models in which the experience and the logical rules of appreciation were used.

The first concept of roundabout arrangement was introduced in Paris (1907) by architect Eugene Alfred Henard.

According to [1] the first use of the British word, "roundabout" was adopted by the UK Transport Ministry. The US and Canadian names of this type of intersection are "traffic circle" or "rotary" in the case of generic geometric arrangements that offered long weaving sections. In the US, the first design guide for these types of fittings was published in 1945 by the American Association of State Highway Officials (AASHO).

After this period of beginning, the old concept of weaving capacities was replaced with the modern concept of the entry capacities. Designing modern roundabouts uses different principles. The key decision was to change circulating traffic priority and began designing roundabouts with smaller diameters to determine the driver to focus on critical access time and follow-up time.

According to [2], since 1966 the British have adopted the "priority-to-the-circle" rule or "YELD" sign at entries. Also, a number of measures have been adopted to reduce the number of accidents, for example, the deflection of traffic through the use of properly designed approaches and exits being one of the characteristics that distinguish the modern roundabout from a traffic circle. A feature of modern roundabouts is the high traffic capacity that is obtained by slightly widening the road at the entry points.

The results of UK researchers have been extended to many countries, including the US. According to [2], the first word of “roundabout” arrived in Michigan in 1995 and [3], the California Department of Transportation converted the Long Beach traffic circle to a modern roundabout in 1993. This conversion was the first of its kind in the US and involved modifications to all entries.

In our country, the roundabouts have seen a widespread development in the last decade both in urban and extra urban areas. The first rule adopted in Romania, dealing with the roundabout intersections [4] provides a method for calculating roundabout circulation capacity with one traffic lane on the ring road, taken from the HCM 2000 (Highway Capacity Manual 2000) [5], and two alternative methods. In order to calculate the circulation capacity of a roundabout with two lanes on the ring road, the Romanian norm wanted to adopt the formula provided by HCM 2010 (Highway Capacity Manual 2010) [6], but this was transcribed erroneously, being impossible to be applied in the norm Offered by the current Romanian standard. This study wants to provide the clarifications needed to apply this formula in good condition.

In Romania, prior to this regulation [4], [7] was used to for designing and analysing the geometry of the traffic capacity of these types of intersections.

At present, the most ambitious achievement in this field in our country is the first suspended roundabout in Romania, inaugurated in May 2016, on the Blejoi locality in Prahova county, at the exit from Ploiesti to Paulesti. The suspended roundabout, which has a unique architecture in Romania, is about one kilometre long and a height of about 7 meters.

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2. ANALYSIS METHODS

According to [5], intersection analysis models generally fall into two categories. Empirical models rely on field data to develop relationships between geometric design features and performance measures such as capacity and delay. Analytical models are based on the concept of gap acceptance theory.

We chose for this paper to present five methods for roundabout circulation analysis that can be grouped into analytical models based on the principle of "gap acceptance theory" and empirically based on the "regression model" principle for the two-lane circulating model. The methods used for this research are described below (Case i … v). Each model equation is presented taking into account the general characteristics of each arm.

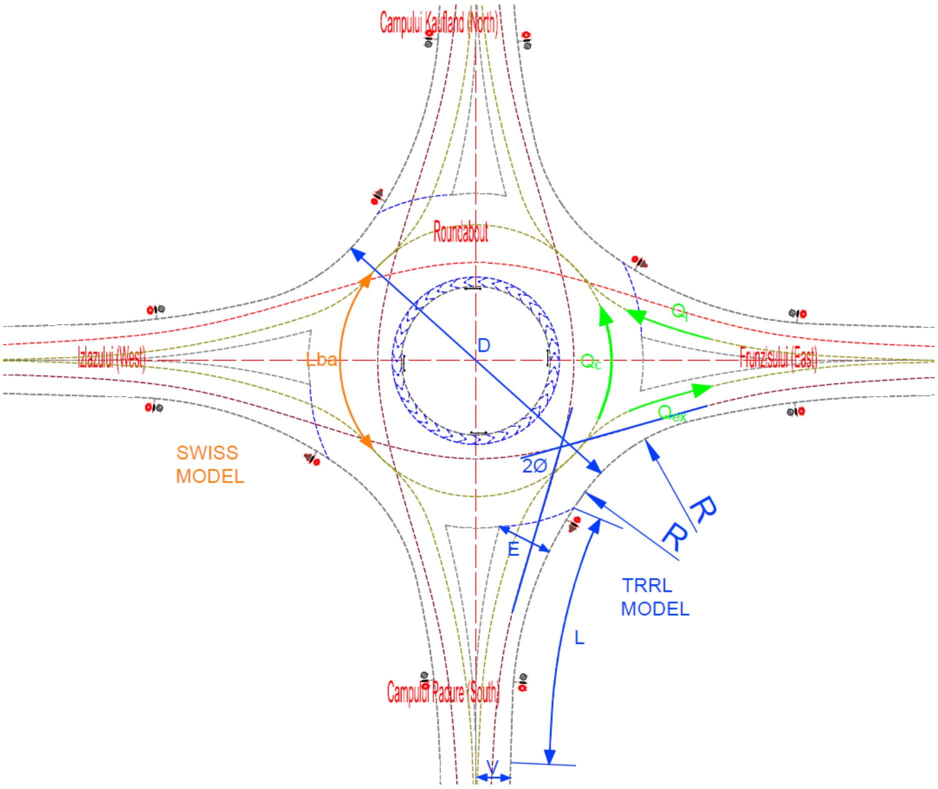

Figure 1. Geometric parameters

2.1. Case i

Case i - R.L.Kimber [8] with the Transport Research Laboratory (T.R.R.L.) development of a capacity model for roundabouts in the U.K. Prediction of

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entering flow or capacity was found to correlate to circulating flow and six geometric parameters:

- entry width (e)
- approach width (v)
- flare length (ℓ, ℓ' - the length over which local widening of the approach is developed)
- entry angle (φ)
- inscribed circle diameter (D)
- the radius of the curb at entry (r)

This formula ("11 Equation") yields a linear relationship between the capacity and the opposing flow. The capacity obtained when the opposing flow is null is named "geometric capacity".

$$Cap = F - f_c * Q_c \tag{11}$$

Where:

- Cap is the entry flow or capacity in pcu/h;
- Q_c is the circulating flow in pcu/h;
- F is the y intercept
- f_c is the slope of the linear regression, are positive constants determined by the equations listed below.

$$k = 1 - 0.00347(\emptyset - 30) - 0.978((1/r) - 0.05)$$

$$F = 303x_2$$

$$f_c = 0.210t_d(1 + 0.2x_2)$$

$$t_D = 1 + 0.5/(1 + \exp((D - 60)/10))$$

$$x_2 = v + (e - v)/(1 + 2S)$$

$$S = (e - v)/l = 1.6(e - v)/l'$$

Where e, v, ℓ, ℓ', D, r are in meters and φ in degrees.

2.2. Case ii

Case ii - The following equations ("12 Equation and13 Equation") presented in the Swiss guide on roundabout design [9] are used to calculate the capacity of the roundabout.

$$Cap = k[1500 - (8/9) * Q_g] \tag{12}$$

$$Q_g = (\beta * Q_c + \alpha * Q_{ex}) \quad (13)$$

Where:

- Cap is the entry flow or capacity in pcu/h;
- Q_c is the circulating flow in pcu/h;
- Q_{ex} is the flow leave the roundabout by the previous exit in pcu/h;
- α is a parameter reflecting the degree of vehicles in the entry disturbed by the vehicles exiting at the same branch, determined based on L_{ba} which is the distance between the diverging point at the exit and converging point at entry;
- κ in this case is 1.4 and it depends on the number of lanes in the entry and
- β is a parameter taking account of multi-lanes in the circulating carriageways, in this case is 0.7.

These two models can be considered empirical, the other tools presented below belong to the group of analytical models based on the concept of gap acceptance theory.

2.3. Case iii

Case iii - The model presented in the German Highway Capacity Manual (HBS 2001) [10] uses gap acceptance theory with critical gap access (tc) and follow-up headway (tf) as the main parameters: number of circulating lanes (nc), number of entry lanes (ne) and minimum gap between succeeding circulating vehicles (tmin). The resulting capacity equation ("14 Equation") is:

$$Cap = 3600\left(1 - \frac{t_{min} Q_c}{3600 n_c}\right)^{n_c} \frac{n_e}{t_f} e^{-\frac{Q_c}{3600}\left(t_c - \frac{t_f}{2} - t_{min}\right)} \quad (14)$$

where

- Cap is the entry flow or capacity in pcu/h;
- Q_c is the circulating flow in pcu/h;
- critical gap (t_c)
- follow-up headway (t_f)
- minimum gap between succeeding circulating vehicles (t_{min}) is in seconds (s).

According to [11], it has come to this solution after considering many approaches, the proposed formula uses Tanner's [12] equation in a form which was adjusted to the necessities of roundabout analysis approach by Wu [13].

2.4. Case iv

Case iv – According to [6], equation (15) gives the capacity of the lanes, respectively, of a two-lane roundabout entry conflicted by two circulating lanes.

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$$Cap_{right} = 1{,}130e^{(-0.7\times10^{-3})Q_c} \quad (15)$$

This model has been developed in the U.S. and it is recommended to be calibrated according to the area in which the roundabout is located and to familiarise users with these types of arrangements. Depending on this, its capacity may increase or decrease.

2.5. Case v

Case v – A simplified formula of eq. 14 in which t_{min} is considered = 0, known as Siegloch's capacity equation [14], has been adopted by the normative frame from Romania [4].

$$Cap = 3600 \cdot \frac{n_e}{t_f} \cdot e^{-\frac{Q_c}{3600}\left(t_c - \frac{t_f}{2}\right)} \quad (16)$$

The last two equations are exponential and the parameters have the same meaning as in the first three formulas.

The extensive documentation on the models developed over time, used in the case study presented in the next chapter, is included in "Table 1". This synthetic analysis includes parameters of each model equation used in microsimulation to highlight the similarities and differences between them.

Table 1. Simulation case

Case	Capacity Equation for two-lane circulating model – Capacity entering flow rate Cap (pcu/h)	Model Equation parameters
Case i	Formula of T.R.R.L. - Empirical Regression Capacity Equation	Circulating flow rate Q_C (pcu/h) Geometric parameters
Case ii	Formula of CETUR	Circulating flow rate Q_C (pcu/h) Exit flow rate Q_{ex} (pcu/h) Distance between diverging point at exit and converging point at entry Number of entry lanes
Case iii	Formula of German Highway Capacity Manual (HBS 2001)	Circulating flow rate Q_C (pcu/h) Number of circulating lanes Number of entry lanes Follow-up headway Gap acceptance (critical gap and minimum gap)
Case iv	Formula of NCHRP 572 / HCM 2010	Circulating flow rate Q_C (pcu/h)

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Case v	Siegloch's capacity equation	Circulating flow rate Q_C (pcu/h) Number of circulating lanes Follow-up headway Critical gap

One can notice that all models use the circulating flow rate as the input date within the circulating capacity calculation formula.

3. COMPARISONS ALTERNATIVE MODELING TOOLS

The roundabout hereinafter referred to as "Câmpului", is located in an urbanised area of Cluj-Napoca in Romania.

The intersection geometry analysed is explained in Table 2.

Table 2. Geometric parameters

Arm	Geometric parameters					
	e (m)	V (m)	l' (m)	D (m)	Φ (º)	r (m)
Arm 1-Frunzisului (East)	5.96	3.5	7.24	36	27.13	20
Arm 2-Campului Padure (South)	5.96	3.5	7.24	36	27.13	20
Arm 3-Izlazului (West)	5.96	3.5	7.24	37	27.13	20
Arm 4- Campului Kaufland (North)	5.97	3.5	7.19	38.26	38.26	20

The modeling was reported in all five cases to the same traffic data in "Table 3", during the peak period of the day set in the range (17.00-18.00), considering the critical gap (t_c= 4,1 s), follow-up headway (t_f = 2,9 s) and minimum gap between succeeding circulating vehicles (t_{min}= 2,1 s).

Table 3. Traffic data

	Entry flow rate Q_i (pcu/h)	Conflicting flow rate Q_C (pcu/h)	Exit flow rate Q_{ex} (pcu/h)	Entry lanes	Number of circulating lanes
Arm 1	602	987	824	2	2
Arm 2	1001	425	723	1	2
Arm 3	733	991	972	2	2
Arm 4	997	708	592	2	2

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In this research, all models behaved similarly with the use of similar traffic data. A slight reserve of traffic capacity was highlighted in the first two cases.

Table 4. Level of service based on Degree of saturation only

		Capacity	Degree of saturation (V_i/Cap ratio)	Level of service
Case i	Arm 1	832.47	0.72	C
	Arm 2	1165.64	0.86	D
	Arm 3	831.70	0.88	D
	Arm 4	1000.08	1.00	E
Case ii	Arm 1	789.78	0.76	C
	Arm 2	369.80	2.71	F
	Arm 3	810.34	0.90	D
	Arm 4	566.64	1.76	F
Case iii	Arm 1	49.01	12.28	F
	Arm 2	295.70	3.39	F
	Arm 3	52.04	14.08	F
	Arm 4	67.46	14.78	F
Case iv	Arm 1	421.14	1.43	F
	Arm 2	738.76	1.35	F
	Arm 3	419.46	1.75	F
	Arm 4	556.67	1.79	F
Case v	Arm 1	536.68	1.12	F
	Arm 2	941.43	1.06	F
	Arm 3	534.54	1.37	E
	Arm 4	709.38	1.41	F

One of the questions that require a response as a result of this modelling is how the user behaves in the future. Do the following parameters change: gap acceptance (critical gap and minimum gap) and follow-up headway so that capability estimates are based on minimum, maximum, or average values? Clearly, there are several issues that require careful thinking to improve waiting times and provide a better understanding of drivers over the prospects of exploiting these types of intersections that will lead to increased traffic and safety.

Data aggregation from the five approaches studied for the "Câmpului" roundabout allowed the determination of control delays for each arm and the determination of the intersection service level, depending on this parameter.

Table 5. Level of service based on Delay only

		Control delay (sec/veh)	Level of service for lane	Delay for the intersection (sec/veh)	Level of service for the intersection
Case i	Arm 1	18.99	B	44.88	D
	Arm 2	24.95	C		
	Arm 3	37.11	D		
	Arm 4	86.23	F		
Case ii	Arm 1	22.52	C	1362.18	F
	Arm 2	3102.46	F		
	Arm 3	43.95	D		
	Arm 4	1393.01	F		
Case iii	Arm 1	20468.54	F	17662.54	F
	Arm 2	4327.69	F		
	Arm 3	23700.78	F		
	Arm 4	24917.26	F		
Case iv	Arm 1	231.97	F	293.15	F
	Arm 2	186.44	F		
	Arm 3	368.94	F		
	Arm 4	381.51	F		
Case v	Arm 1	103.41	F	145.73	F
	Arm 2	68.14	F		
	Arm 3	200.79	F		
	Arm 4	208.68	F		

During this study, many problems have been identified that require further research, especially with regard to control delays where it has not really been proven that there is a related queue of this length to justify the values obtained from modelling. Even long queues tended to advance so there are questions about defining delays.

3. CONCLUSIONS

Given the significant traffic increase in Romania, the use of roundabouts has become one of the most attractive types of intersections in both urban and extra urban areas.

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The implementation of this type of arrangement requires the choice of the most suitable instrument, calibrated according to the area in which the roundabout is located, the geometric elements of the arrangement and familiarisation of the users with this type of intersection, for the calculation of the traffic capacity.

In chapter 2 we present five procedures for analysing roundabouts, introduces the unique characteristics of roundabout capacity and presents terminology specific to roundabouts.

Due to the in-depth analysis, we have been able to determine the transcription error, existing in the formula presented by the normative framework in Romania and we make suggestions, on this occasion, to remedy it.

Both models known in the literature, Regression models and Analytical models were described and then used as modelling tools in chapter 3 of the study for the "Câmpului" roundabout in Cluj-Napoca.

All models use the circulating flow rate as the input data within the circulating flow calculation formula. Slightly permissive results from the point of view of the circulation capacity were obtained with the empirical models. During this study, identified problem, especially with regard to control delays where it has not really been proven that there is a related queue of this length to justify the values obtained from modelling.

This research provides a scientific perspective regarding the optimal tool for calculating the circulation capacity of the roundabouts, but choosing the direction of the analysis is a complex decision that depends on several factors and needs to be well managed.

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