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SIMULATION MODELLING OF PEDESTRIANS INFLUENCE ON THE ROUNDABOUT CAPACITY

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Abstract
Pedestrians in general have priority to the cars on unsignalized intersections and roundabouts. Roundabout capacity highly depends on pedestrians, which can interrupt traffic flow whenever they step on the crosswalk. If there are pedestrian crossings on each approach, vehicles should stop to allow them to cross the road. In some cases, vehicle stopped on the exiting lane can even block the central circle of the roundabout, causing serious deterioration of the capacity and level of service. Position of the crosswalk on the entering and exiting lane can reduce influence of pedestrian interruption of car flow. Analysis of pedestrian influence on exiting lane capacity has not been researched before and the aim of this paper is to show how pedestrian flow and the crosswalk location influence on the roundabout capacity and level of service. In addition, comparison of the crosswalk location related to the centre of the roundabout was given.
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Key Words: Roundabout Capacity, Pedestrians, Crosswalk, Simulation, Intersection Approach

1. INTRODUCTION

Roundabouts are generally safer than unsignalized and signalized intersections. Roundabouts are a preferred choice for traffic safety due to their reduced conflict points and slower speeds, making them an ideal option for implementing traffic regulations. On the other hand, it should be noted that while roundabouts have numerous advantages for traffic safety, they are not completely immune to disruptions. One potential challenge arises from pedestrian flow, which can interrupt the smooth flow of vehicles at any given time. These interruptions can occur both on the entry lanes, where pedestrians may be crossing the road, as well as on the exit lanes, where pedestrians may be waiting to cross to the other side. Thus, it is important for traffic regulations to address and manage these potential conflicts between pedestrians and vehicles at roundabouts to ensure the overall safety and efficiency. Roundabouts' capacity and level of service are the subjects of many research [1, 2]. A mathematical model for capacity analysis is given in the paper written by Suh et al. [3] and Zhang et al. [4]. Congestion analysis based on Multi-Layer Time-Varying Network was subject of paper written by Huang et al. [5]. All issues of the Highway Capacity Manual (HCM), beginning with HCM2000 [6], define procedures for roundabout capacity analysis just for single-lane roundabouts. The next version of the same manual HCM2010 [7] defined a slightly different methodology for single-lane roundabouts and a new methodology for two-lane roundabouts. The latest HCM 6th edition [8] gave corrected values of the capacity analysis procedure in HCM2010. The last two versions of HCM introduced an addition for critical headway and follow-up headway methodology using the adjusted Siegloch formula for capacity analysis [9]. Similar studies are given in the papers written by Wu and Brilon [10] and Guo et al. [11]. Comparative analysis of two roundabout capacity models developed in Poland and Australia were given in the paper by Macioszek and Akçelik [12]. Paper written by Ibrahim et al. [13] gives simulation of pedestrian behaviour.

With the increasing complexity of human problems and expectations over time, the world has entered a technological era where constant efforts are being made to create machines that are smarter or equally intelligent as humans [14]. The advancement of computer technology, mobile communication technology, big data, artificial intelligence, deep learning, Artificial Intelligence of Things (AIoT), and other emerging technologies have introduced innovative solutions and approaches for addressing many traffic problems [15]. In their paper, Fernandes et al. [16] did a multicriteria assessment of midblock crosswalk location between two roundabouts. Evaluating the performance of an any system under conditions that closely resemble real-life situations is most effectively done through simulation [17]. Using microsimulation, they have determined the influence of pedestrian crosswalks on traffic delay, carbon dioxide emissions, and relative speed between vehicles and pedestrians at different locations between closely spaced roundabouts.

The aim of this paper is to show how pedestrian flow and the crosswalk location influence on the roundabout capacity and level of service. Major contribution of this paper is analyses which was not done before, regarding real capacity of exiting roundabout lane. All analyses were made using drone video recording of roundabouts and microsimulation software. In addition, comparison of crosswalk position and recommendation for the optimal position of the crosswalk was given.

2. PROBLEM DESCRIPTION

The capacity of the entering lanes in a roundabout is determined by the flow of conflicts that circulate into the central circle, as well as the impedance caused by pedestrians crossing those lanes [8]. The level of impedance experienced is directly influenced by the number of pedestrians crossing these entering lanes. It is crucial to consider this factor when evaluating the capacity of the entering lanes in roundabouts. On the other hand, the capacity of roundabout exit lanes is typically estimated to be around 1200-1300 vehicles per hour. However, it is important to note that according to the HCM, this capacity estimation is not subject to any specific analysis. In real-world scenarios, a common issue arises when vehicles on the exit lanes block the central circle while waiting for pedestrians to safely cross the roadways. This problem becomes even more noticeable in roundabouts with just one circulating lane and one exit lane. This typical case is shown in Figure 1.

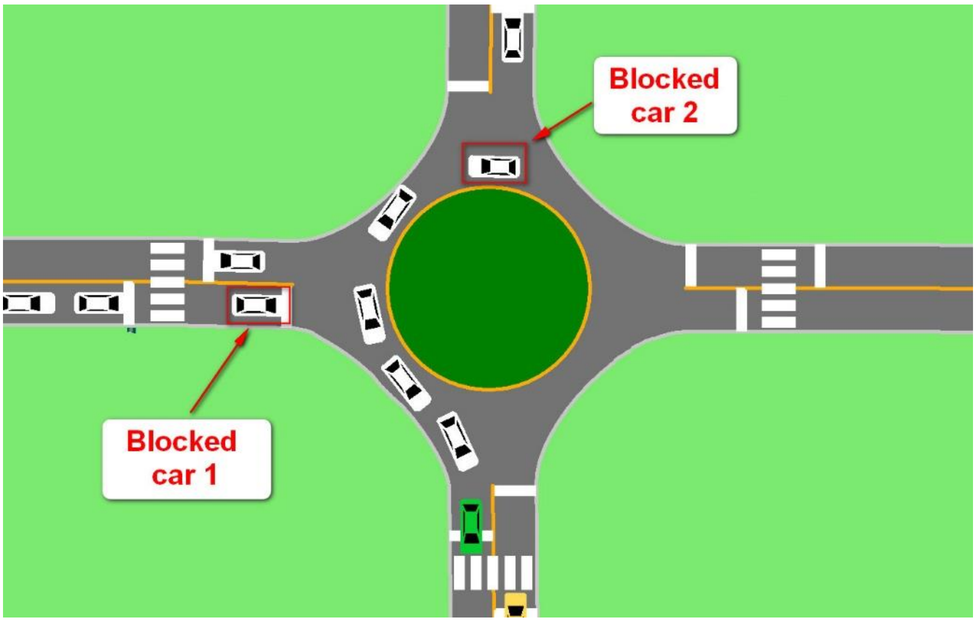

Figure 1: Pedestrians blocking the exiting lane.

The issue of a blocked exit lane in a roundabout is not only related to the capacity of that specific lane but rather to the overall capacity of the roundabout. When cars on the exit lane are blocked, it directly affects the capacity of the roundabout. The blockage caused by vehicles waiting for pedestrians to cross the roadways results in reduction of traffic flow within the central roundabout circle. Consequently, the reduced capacity of the roundabout can lead to congestion, delays, and inefficient utilization of the available capacity. Problem of blocked exit lanes can be partially solved by positioning crosswalks far from central island which was analysed in this paper.

3. RESEARCH

For this research, two roundabouts are recorded using drones for 2 hours each. They are recorded in the period when pedestrians are present (first hour) and when there were not many pedestrians (second hour). Practical capacity was measured in a case where constant queue conditions were present. The main geometric and traffic characteristics of analysed roundabouts were:

1. One circulating lane,
2. One entering lane at all approaches,
3. One exit lane at all approaches,
4. No bypass lanes,
5. Crosswalks at all approaches,
6. No heavy vehicles,
7. Queue conditions at every approach for at least 15 min (for practical capacity measurement).

The layout of the analysed roundabouts is given in the following figures (Figure 2 and Figure 3).

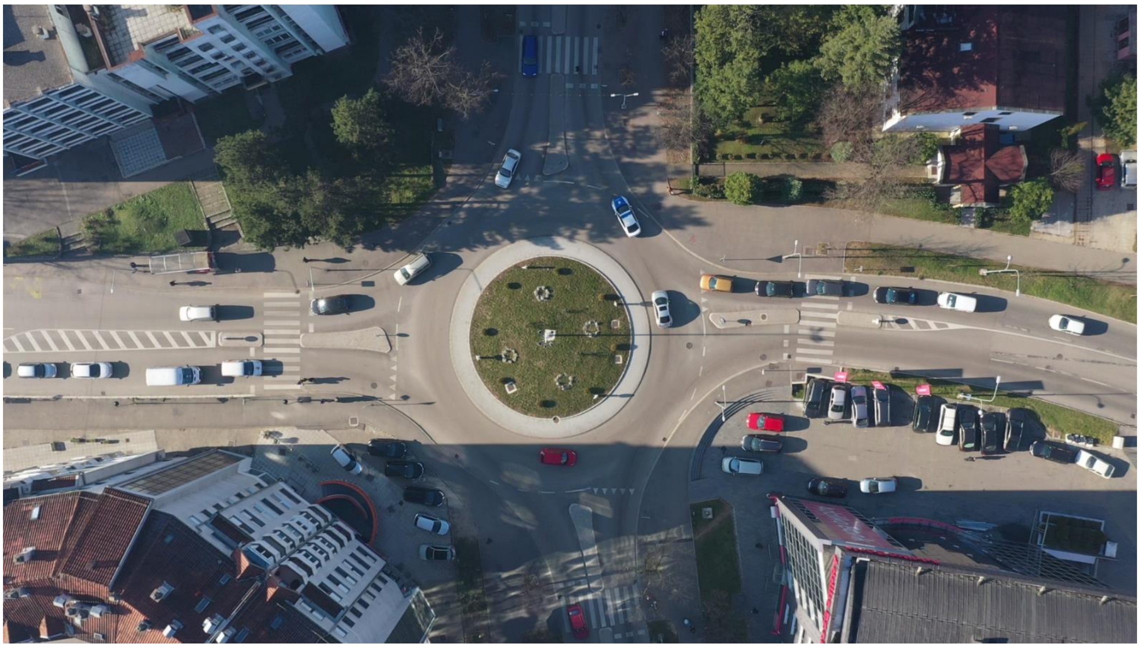

Figure 2: Analysed roundabout 1.

The problem at both analysed roundabouts was the blockage of the circulating lane by vehicles stopped to let pedestrians pass the crosswalk at the exit lane.

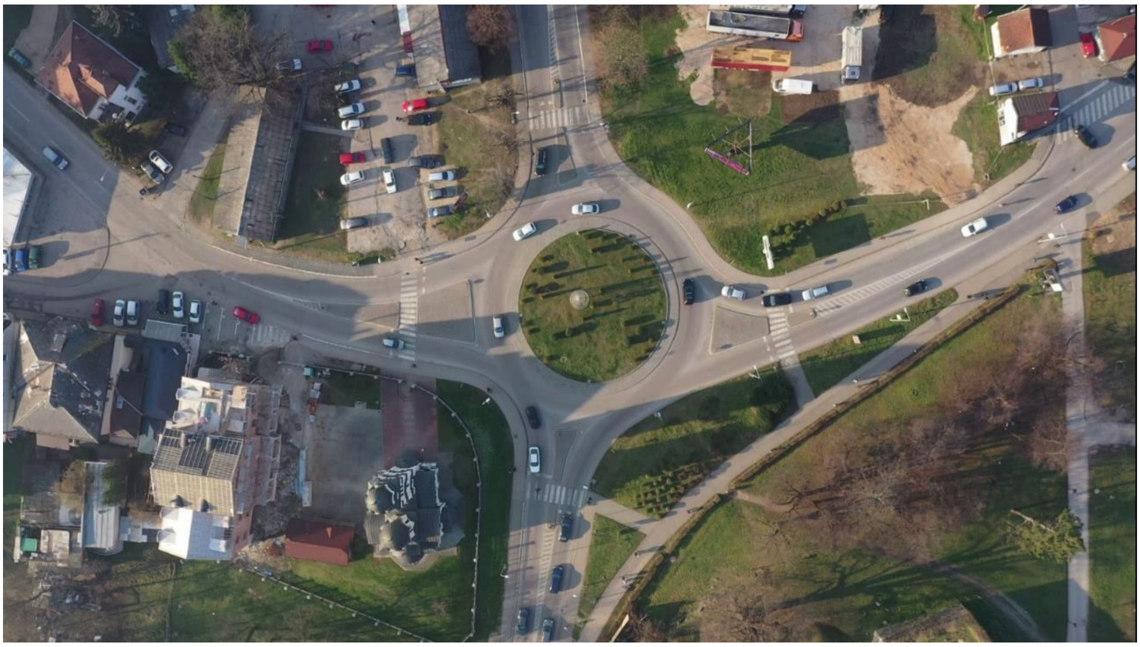

Figure 3: Analysed roundabout 2.

Figure 4: Vehicles at the east approach stopped due to a blocked circulating lane.

As shown from previous figures, both analysed roundabouts have pedestrian crossings close to the circulating lane. The position of the crosswalks will be investigated later in this paper. Traffic and pedestrian counting were made for peak hours at all approaches. Results are given in the following two tables.

Table I: Values of traffic and pedestrian flow at the Roundabout 1.

Approach	Traffic volume (veh./h)		Pedestrian volume (ped./h)
South	Left	162	241
	Through	453	
	Right	85	
East	Left	21	227
	Through	357	
	Right	245	
North	Left	198	186
	Through	317	
	Right	249	
West	Left	142	132
	Through	407	
	Right	196	

Table II: Values of traffic and pedestrian flow at the Roundabout 2.

Approach	Traffic volume (veh./h)		Pedestrian volume (ped./h)
South	Left	124	107
	Through	265	
	Right	235	
East	Left	205	244
	Through	197	
	Right	77	
North	Left	9	146
	Through	287	
	Right	34	
West	Left	17	150
	Through	120	
	Right	201	

According to HCM2016 [8], the capacity of a roundabout's approach where the entering lane is conflicted with one circulating lane is calculated using Eq. (1):

$$C_{e,pce} = 1380 \cdot e^{(-1{,}02\times 10^{-3})v_{c,pce}} \tag{1}$$

where:

$C_{e,pce}$ – base capacity of entering lane at the roundabout, without the influence of pedestrian or heavy vehicles,

$v_{e,pce}$ – conflict flow for entering lane at the roundabout.

Pedestrian impedance for roundabouts, which are analysed using values of the counted number of vehicles per hour, is calculated using Eq. (2):

$$f_{ped} = \frac{1119.5 - 0.715v_{c,pce} - 0.644n_{ped} + 0.00073v_{c,pce}n_{ped}}{1068.6 - 0.654v_{c,pce}} \tag{2}$$

where:

f_{ped} – pedestrian influence factor on the roundabout approach capacity,

n_{ped} – number of pedestrians at the roundabout approach.

In addition, the adjusted capacity of the entering lane is:

$$C_e = C_{e,pce} \cdot f_{hv} \cdot f_{ped} \tag{3}$$

where:

C_e – entering lane capacity,

f_{hv} – heavy vehicles influence factor.

The theoretical capacity of each entering lane is calculated using Eqs. (1) to (3) and it was given in the following tables (Table , Table). It was assumed that f_{hv} is 1 because there are no heavy vehicles at the roundabouts.

Table III: The theoretical capacity of entering lanes at the roundabout 1.

Approach	Conflict volume (veh./h)	f_{ped}	Theoretical capacity (veh./h)
South	747	0.97	633
East	757	0.97	629
North	540	0.96	772
West	536	0.98	790

Table IV: The theoretical capacity of entering lanes at the roundabout 2.

Approach	Conflict volume (veh./h)	f_{ped}	Theoretical capacity (veh./h)
South	146	0.98	1174
East	406	0.93	853
North	526	0.97	794
West	501	0.97	812

Calculated values of f_{ped} show that pedestrians do not significantly influence the approach capacity. In order to measure practical capacity, traffic counting in **constant queue** conditions was made. This approach to capacity determination shows values of practical capacity. Namely, if the traffic counting was made in constant queue conditions, that represents the maximum number of vehicles which can enter the intersection. Using on-field measurements, the following practical capacities were determined.

Table V: The theoretical capacity of approaches at the analysed roundabouts (veh./h).

Approach	Roundabout 1			Roundabout 2		
	Practical capacity	Theoretical capacity	**Capacity utilization**	Practical capacity	Theoretical capacity	**Capacity utilization**
South	427	633	**67 %**	529	1174	**45 %**
East	455	629	**72 %**	664	853	**78 %**
North	531	772	**69 %**	483	794	**60 %**
West	563	790	**71 %**	559	812	**68 %**
Total	**1976**	**2824**	**-**	**2235**	**3633**	**-**

As can be seen in Table V, the theoretical capacity calculated using the HCM methodology is much larger than the practical capacity under constant queue conditions. This stark contrast between the two measurements indicates a notable shortcoming in the HCM methodology, particularly when applied to specific conditions. Through extensive research conducted for this paper, it was discovered that the reduction in capacity resulting from blockage of the circulating lane is far more substantial than previously accounted for, reaching up to a staggering 30 % when compared to the theoretical capacity predicted by the HCM methodology. This discrepancy highlights the need for further refinement and enhancement of the existing model to accurately capture the impact of blockages on traffic flow. Furthermore, the influence of pedestrians, as expressed in Eq. (2) of the HCM methodology, was found to be significantly underestimated when compared to real-world observations. The measured impact of pedestrians on traffic flow exceeded the predictions made by the HCM model, suggesting that additional factors or variables should be considered to account for pedestrian behaviour more accurately. Another limitation in the HCM methodology pertains to the lack of consideration for the influence of pedestrians at the exit lane.

4. SIMULATION MODELLING

In order to determine the influence of the pedestrians at the exit lane, a simulation in Trafficware Synchro/Simtraffic was made. Synchro uses HCM methodology for all types of intersections (unsignalized, signalized and roundabouts) to determine operational characteristics and level of service for vehicles (average delays). This software is very good for optimization of signal timings at the signalized intersections, as well as to determine level of service and queues at unsignalized intersections and roundabouts. Simtraffic, on the other hand has dynamic traffic conditions, representing real traffic flow, which include cars, trucks, buses, and pedestrians on the network. Delays, vehicular queues, travel times and other measures of effectiveness are computed for network as well as for individual intersections or approaches. In a defined simulation period network performance can be determined for roadway segments and corridors, in addition to individual intersections. Simtraffic module has 2D and 3D animations including each parameter which describes the traffic conditions on defined network.

A simulation was made for two typical cases to determine real capacity and analyse if the location of pedestrian crossing influences the blockage of the circulating lane. Analysed cases were:

- **Case 1.** The crosswalk is very close to the circulating lane.
- **Case 2.** The crosswalk is at least 30 m of circulating lane.

The layout of the cases is given in the following figures (Fig. 5, Fig. 6).

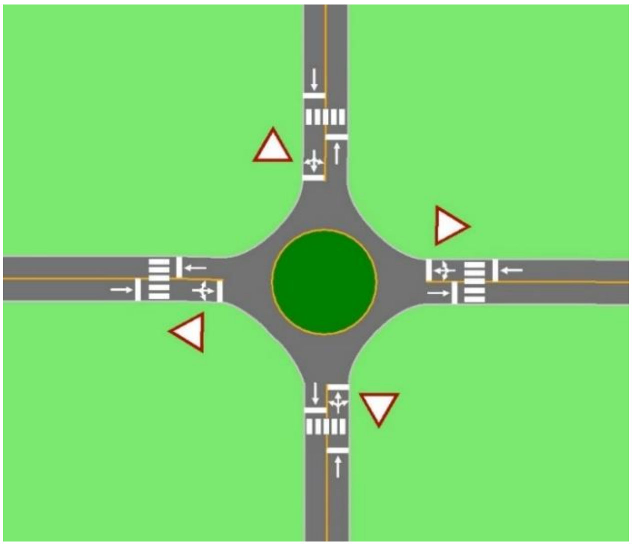

Figure 5: Case 1 – close crosswalk.

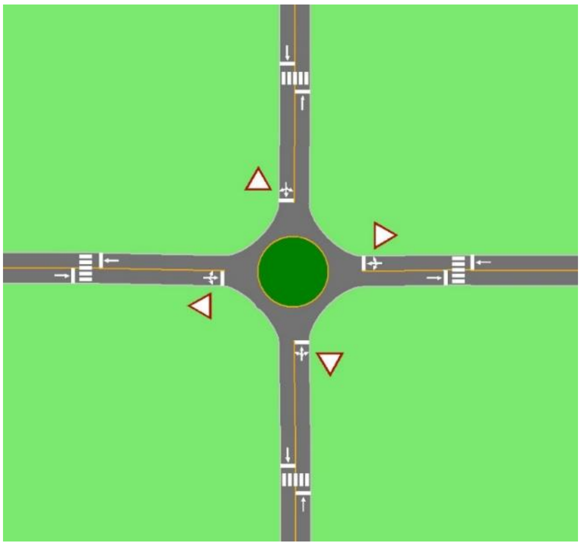

Figure 6: Case 2 – distant crosswalk.

For the simulation modelling, actual data on the number of vehicles and pedestrians gathered from on-field observations were utilized. In the initial stage of the simulation, the assumption was made that no pedestrians were present at the approaches, while in the subsequent stage, a separate simulation was conducted incorporating real pedestrian flow data. This approach allowed for a comparison of the capacity of the approaches with and without pedestrians, enabling the assessment of the impact of pedestrian presence on traffic flow. For this paper, the presented values are for Roundabout 1. It is important to highlight that very similar results were obtained for Roundabout 2, suggesting a consistent pattern across both roundabouts.

3: Performance by lane

Lane	EB	WB	NB	SB	All
Movements Served	LTR	LTR	LTR	LTR	
Denied Delay (hr)					0.0
Denied Del/Veh (s)					0.0
Total Delay (hr)	0.7	0.7	0.9	0.7	3.0
Total Del/Veh (s)	3.8	3.8	6.9	3.6	4.3
Vehicles Entered	686	611	445	742	2484

Figure 6: The capacity of all approaches **without** pedestrians (close crosswalk).

3: Performance by lane

Lane	EB	WB	NB	SB	All
Movements Served	LTR	LTR	LTR	LTR	
Denied Delay (hr)					0.0
Denied Del/Veh (s)					0.0
Total Delay (hr)	0.7	0.6	0.7	0.6	2.6
Total Del/Veh (s)	4.9	4.1	6.2	3.6	4.6
Vehicles Entered	541	527	393	609	2070

Figure 8: The capacity of all approaches **with** pedestrians (close crosswalk).

3: Performance by lane

Lane	EB	WB	NB	SB	All
Movements Served	LTR	LTR	LTR	LTR	
Denied Delay (hr)					0.0
Denied Del/Veh (s)					0.0
Total Delay (hr)	3.1	1.8	3.4	2.8	11.1
Total Del/Veh (s)	17.2	9.9	23.4	16.3	16.3
Vehicles Entered	647	660	518	626	2451

Figure 9: The capacity of all approaches **without** pedestrians (distant crosswalk).

3: Performance by lane

Lane	EB	WB	NB	SB	All
Movements Served	LTR	LTR	LTR	LTR	
Denied Delay (hr)					0.0
Denied Del/Veh (s)					0.0
Total Delay (hr)	2.9	1.7	3.2	2.5	10.3
Total Del/Veh (s)	16.5	10.2	25.7	14.6	16.2
Vehicles Entered	635	584	438	618	2275

Figure 10: The capacity of all approaches **with** pedestrians (distant crosswalk).

Based on the previous findings, the capacity of a roundabout is affected by the proximity of crosswalks to the circulating lanes and the presence of pedestrians. When the crosswalk is located close to the circulating lane with no pedestrians, the practical capacity of the roundabout is 2484 vehicles per hour. However, when pedestrians are present, the capacity decreases to 2070 vehicles per hour, resulting in a reduction of 17 %.

On the other hand, when the crosswalk is positioned further away (over 30 meters) from the circulating lane, the capacity without pedestrians is 2451 vehicles per hour. With pedestrians, the capacity decreases to 2275 vehicles per hour, representing a reduction of about 7 %. It's important to note that the same traffic and pedestrian flow values were used for both analyses.

The difference between these two situations is significant, with a variation of over 200 vehicles per hour or approximately 10 % in capacity. This highlights the impact that pedestrian presence and the location of crosswalks can have on the overall capacity and efficiency of a roundabout. By considering these factors in traffic planning and implementing appropriate measures, such as strategic crosswalk placement and pedestrian management strategies, it is possible to optimize roundabout capacity and improve traffic flow.

5. DISCUSSION

Pedestrian influence on the capacity of the roundabouts is given in the HCM just for entering lanes (approaches). However, on-field measurements showed a much more significant pedestrian influence than the value calculated using the HCM formula for f_{ped}. On the other hand, the influence of pedestrians on roundabouts capacity is not valued for exiting lanes. On-field observation showed that pedestrians crossing exit lanes could very often block that lane, leading to blockage of cars in the circulating lane. This problem can be severe at one-lane roundabouts (roundabouts with one circulating lane, one entering, and one exiting lane). All previously stated shows that blockage of exit lane can lead to blockage of circulating lane, which can significantly reduce the capacity of a roundabout and level of service. Pedestrian influence at the exiting lane can block the whole roundabout, while on entering approach can block only that approach.

For two analysed roundabouts, capacity and pedestrian influence were determined. The HCM formula calculated that pedestrian influence in the interval of 107-244 ped./h is between 0.93 and 0.98. These values reduce capacity in a little break (2-7 %).

On-field measurements showed different values of capacity reduction. Theoretic capacity values (calculated using HCM formulas) differ from 629-1174 vehicles per hour per approach, or 2824-3633 vehicles per hour for a roundabout, while practical capacity is between 427 and 664 vehicles per hour per approach or 1976-2235 vehicles per hour for a roundabout. Analysed values show an almost 30 % difference between theoretical and practical capacity with the influence of the pedestrians.

Using microsimulation software Synchro/Simtraffic, more realistic capacity values were determined. According to the simulation, the capacity of the roundabout without pedestrians' influence was 2484 vehicles per hour, while with pedestrians' influence, this capacity was 2070 vehicles per hour. This value (2070 vehicles per hour) is much more realistic and closer to real on-field capacity (1976 vehicles per hour) than the theoretically calculated value of 2824 vehicles per hour. This analysis showed that pedestrian influence is about 17 % in capacity reduction, which is much more than 2-7 %, as calculated by the HCM formula. The first analysis was made for the actual position of crosswalks close to the circulating lane (not more than 10 m).

In addition, one more case was analysed to evaluate the influence of the crosswalk position on the capacity. It was assumed that the position of crosswalks could positively influence the capacity because of the larger gap for making queue at the exiting lane.

If the crosswalk is at least 30 m away from the circulating lane, it makes space for 5-6 cars waiting for pedestrians to cross the crosswalk at the exiting lane. This configuration can reduce the possibility of circulating lane blockage.

Simulation of this case showed that if a crosswalk is not so close to the circulating lane, it can improve the approaches and roundabout capacity. Namely, the capacity of the roundabout in the second case was 2451 vehicles per hour without pedestrians, while the influence of pedestrians rose to 2275 vehicles per hour for the same values of traffic and pedestrian flows. This shows an improvement of 200 vehicles per hour compared to the case where crosswalks are close to the circulating lane. Besides that, in this case, the reduction in capacity is about 7 %, which corresponds to the values calculated by HCM.

According to the HCM, the capacity of the exiting lane is between 1200-1300 veh./h. The simulated environment showed much smaller values of the capacity. Values obtained by simulation are shown in Table .

Table VI: Values of the exiting lane capacity.

Approach	**Capacity (close crosswalk)**	**Capacity (distant crosswalk)**	**Difference**
South	393	438	+11 %
East	498	576	+16 %
North	577	607	+5 %
West	541	635	+17 %

The comparison presented in the previous table highlights two notable findings. Firstly, the actual capacity of the exiting lane is considerably lower than the values projected by the HCM methodology, amounting to nearly half of the assumed capacity range (400-600 veh./h versus 1200-1300 assumed by HCM). This significant disparity underscores the need for a more accurate assessment of exit lane capacity in traffic flow analysis. Secondly, the study reveals that relocating the crosswalk from the circulating lane to an alternative position can lead to a noteworthy improvement in exit lane capacity. This improvement ranges between 5 % and 17 %, showcasing the positive impact of strategic adjustments to pedestrian infrastructure on overall traffic flow efficiency. These findings emphasize the potential benefits of carefully considering pedestrian-related factors when designing and optimizing road systems.

6. CONCLUSIONS

Pedestrians significantly impact the functionality and efficiency of roundabouts as they operate independently of traffic signals and rules. At roundabouts, pedestrians are granted the right of way, and vehicles are required to yield to them at crosswalks under any circumstances. The HCM provides models and formulas for analysing the influence of pedestrians on the capacity of entering roundabout lanes. However, it has been observed that the theoretical values obtained from these models do not align with the actual measurements taken in real-world scenarios. In fact, the disparity between theoretical and measured values exceeds 30 %, indicating a significant deviation that cannot be overlooked.

Furthermore, it is important to note that the HCM does not offer a comprehensive capacity analysis for exiting lanes affected by pedestrians. Recognizing this gap, the present paper undertook the task of measuring the real-world pedestrian influence and its impact on the capacity of both entering and exiting lanes. The study revealed that the actual capacity of entering lanes is consistently 10-30 % lower than the theoretical estimates derived from the HCM. Similarly, the capacity of exiting lanes was found to be significantly reduced, with values dropping by as much as 50 %.

In addition to examining the capacity implications, the paper also investigated the positioning of crosswalks and their relationship to the overall capacity and level of service. The analysis revealed that the placement of crosswalks at a greater distance from the roundabout can potentially enhance the capacity of a given approach by up to 10 %. This finding suggests that strategic placement of crosswalks plays a vital role in optimizing the flow of both vehicular and pedestrian traffic, thus improving the overall efficiency of the roundabout.

By providing concrete measurements of pedestrian influence on roundabouts and uncovering the discrepancies between theoretical and observed capacities, this study contributes valuable insights to the field of transportation planning and design. The findings underscore the necessity of considering pedestrians in capacity analyses and emphasize the importance of accurately accounting for their impact on the functionality of roundabouts. With this knowledge, transportation engineers and urban planners can make more informed decisions when designing and optimizing roundabouts to accommodate the needs of all road users, ensuring safer and more efficient traffic flow.

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