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ROUNDABOUT ARM CAPACITY DETERMINED BY MICROSIMULATION AND DISCRETE FUNCTIONS TECHNIQUE

ABSTRACT

The paper demonstrates the influence of the multi-channel pedestrian flow on the actual capacity of the one-lane roundabout, using micro-simulation and discrete functions. The proposed model is based on the theory of the expected time void between the units of pedestrian traffic flow, which have the priority when crossing the arm of the roundabout. The proposed model represents an upgrade of the previous research in the field of modelling traffic flows in the one-lane roundabout. Beside multi-channel pedestrian flow the disturbances caused by the circular traffic flow of motorised vehicles at the roundabout are also considered. In this way the model can illustrate the real conditions in traffic better. A simulation analysis has been performed on the roundabout's arm at Koroška Street in Maribor. The results of the analysis have indicated a relatively high reserve of the actual throughput capacity for the main motorized traffic flow in the analysed roundabout's arm. The presented model represents a practicable and adaptable tool for planning the roundabout capacity in practice and for the sensitivity analysis of individual variables on the throughput capacity of the roundabout.

KEY WORDS

roundabouts, traffic flow analysis, micro-simulation modelling, capacity analysis

1. INTRODUCTION

Use of roundabout instead of traffic signals or priority intersections is increasing and is becoming the frequently used type of road junctions. According to the Centre for Transportation Research & Training [1], roundabouts have been shown to reduce injury accidents as much as 76 % in the USA, 75 % in Australia and 86 % in Great Britain. The reduction in accidents is attributed to slower speeds and reduced number of conflict points. There are additional benefits of using roundabouts such as elimination of maintenance costs associated with traffic signals. In addition, electricity costs are reduced. By yielding at the entry rather than stopping and waiting

for a green light, delay is significantly reduced. Intersections with a high volume of left turns are better handled by a roundabout than a multi-phased traffic signal. A reduction in delay corresponds to a decrease in fuel consumption and air pollution [1].
The performance of roundabouts is affected by traffic and geometrics features of roundabouts. Design of roundabouts in a sense of determining the capacities and delays is achieved by using empirical or analytical approaches. Empirical approaches rely on field data to develop performance measures such as capacities and delays (mostly used in Europe and UK). Among simple methods where only a diagram or one equation is used are the German method for determining the pedestrian influence [2] and the Dutch method for determining the cyclist influence [3] on the throughput capacity of the one-lane roundabout. On the contrary analytical models are based on gap acceptance theories that attempt to predict capacity on the basis of acceptable gaps and vehicle move up times at priority intersections. Two major groups of methods for determining the capacity of a roundabout and the resulting influences of pedestrian and cyclist flows on the roundabout capacity have been dominant lately. The first group consists of deterministic and the second group of stochastic methods. It must be emphasised that the significance of simulation methods is also increasing, with most credit going to more and more capable computers and numerous possibilities of creating complex mathematical models that enable a good comparability of results with authentic models. Several simulation programs like Rodel, Paramics, Vissim, Synchro, Sidra [4], [5], [6], [7], etc. offer variants of the roundabout analysis based on either the gap acceptance or empirical approaches.

In this paper the influence of the multi-channel pedestrian flow on the capacity of the one-lane roundabout, using micro-simulation and discrete functions is analysed. For the presented problem the computer tool AutoMod [8] has been used. Although the chosen code is not specialised for traffic simulation, the discrete simulation algorithm is very efficient for analysing different situation events. The simulation model is based on the theory of the expected time void between the units of pedestrian traffic flow, which have the priority when crossing the arm of the roundabout. The proposed model represents an upgrade of the previous research in the field of modelling traffic flows in the one-lane roundabout [9], [10], [11], [12]. While the previous model of the pedestrian crossing is handled as the single-channel system in which the pedestrians arrive randomly from one side of the pedestrian crossing only, the proposed model deals with the multi-channel system in which the pedestrians arrive randomly from both sides of the pedestrian crossing. In this way the mathematical model can better illustrate the real conditions. The previous model considers only the disturbances of entry traffic flow of motorised vehicles caused by the pedestrian flow crossing the roundabout arm. The proposed model considers the disturbances caused by the circular traffic flow of motorised vehicles as well. A simulation analysis has been conducted on the roundabout at Koroška Street in Maribor, in which the counting of the motorised traffic flow and the pedestrian flow has been performed due to model calibration. The proposed procedure presented in our paper, along with scientific approach to simulation modelling, represents the procedure for the calculation of the actual capacities in roundabouts.

2. PROBLEM DESCRIPTION

When defining the reduction of the roundabout capacity because of the pedestrian flow crossing the arm of the roundabout, two different samples can be distinguished. In the first case, the traversing pedestrian flow influences the capacity of the roundabout, but it still works. In the second case, the influence of the pedestrian flow is so large that bottlenecks on roundabout entry and exit are possible, which could also be extended to the adjacent roundabout arms.

The abovementioned problems of entering and exiting a roundabout normally appear simultaneously in a real situation. Under real circumstances it is also usual for the intensive pedestrian flow to traverse only one arm of the roundabout, although in some cases the pedestrian flow traverses all arms at once. In these cases the blockage of the roundabout is easier to occur [10], [11], [12].

Figure 1. Queue formation in a roundabout [9]

In the continuation, an example of roundabout where the strong pedestrian flow traverses only one arm is described in order to make it easier to explain. The priority pedestrian flow traverses the (southern) arm of the roundabout (see Figure 1). Time interspaces between two consecutive pedestrians are long enough; therefore the vehicles exiting the roundabout make use of them and exit the roundabout without disruption. The vehicle flow on the exit is stable in this case.
With an increase in pedestrian flow, time interspaces between traffic flow units are reduced. Occasionally situations occur where individual time interspaces between pedestrian flow units are shorter than is acceptable. In these cases the vehicle waits in the waiting place between the outside edge of the circulatory roadway and the inside edge of the pedestrian crossing. The flow is still stable, but occasionally disrupted. The blockage is transferred from the exit towards the preceding entry to the roundabout (inversely to the direction of driving) and from here towards the preceding exit. The entire procedure can occur again and again in the inverse direction of driving until the roundabout is completely blocked. In the one-lane roundabout with waiting space for one vehicle only the following three situations can generally occur in the waiting place between pedestrian crossing and the outer edge of the circulatory carriageway:

- time interspaces between individual units of the traversing pedestrian flow are sufficient for the vehicle flow, therefore there are no waiting vehicles in the waiting place;
- time interspaces between individual units of the traversing pedestrian flow are still sufficient for the vehicle flow, although vehicles do wait in the waiting place;
- time interspaces between individual units of the traversing pedestrian flow are not large enough, the waiting place is occupied all the time and every next vehicle waits in the circulatory roadway.

How many times these situations occur, what are the conditions for the occurrence of these situations, what conditions have to be fulfilled for a blockage of one roundabout arm and at what traffic load of pedestrians or motorised traffic flow the disturbance is transferred from one to another arm are the questions, the answers to which determine the influence of the pedestrian flow on the capacity of the one-lane roundabout. It is obvious that so complex influences and mutual actions of different variables cannot be solved without appropriate mathematical models or discrete simulations of motorised and non-motorised traffic flow. In the following sections the roundabout as a queue system, the simulation model and the analysis of the actual capacity in the selected roundabout's arm at Koroška Street in Maribor are presented.

3. ROUNDABOUT AS A QUEUE SYSTEM

When planning a roundabout, its capacity in relation to the traffic flow (*i*) of Personal Car Units (PCU) and (*ii*) pedestrians is predominantly the main point of interest. The general rule of all roundabouts is that pedestrians are always given priority over the motorised traffic flow. When determining the capacity of a roundabout, the rates of PCU_i and pedestrian flows, crossing each other on an individual arm of the roundabout, are used. The total capacity of PCU_i and pedestrian flows in an individual arm of the roundabout can be presented with the following simplified relation dependence. The arrivals of PCU and pedestrian flows in the individual arm of the roundabout can be treated as a queuing system with one serving place [13]. When determining the appropriate system of the waiting line, the basic condition that the arrivals of PCU are distributed according to *Poisson's statistical distribution* is taken into account. The condition that the time between two arrivals of pedestrians is distributed according to *exponent statistical distribution* is also considered. Due to the connection between *Poisson's* and *exponential statistical distribution*, the following relation has to be defined. If the number of PCU and pedestrian arrivals in a given time interval t is distributed according to *Poisson's statistical distribution* with an average degree of arrivals in a time unit λ and a medium value $\lambda \cdot t$, then the time intervals between the arrivals of two consecutive PCU and pedestrians are distributed according to the *exponent statistical distribution* with a medium value of $1/\lambda$. The relations in the roundabout can be represented with the following expressions:

M	–	refers to *Poisson's* distribution of PCU and pedestrian arrivals in a given time unit
M	–	refers to *Poisson's* distribution of time, required for the driving of PCU over the pedestrian crossing and the crossing of pedestrians to the other side of the roadway
s	–	only one serving station exists the system, which is connected to the pedestrian crossing
∞	–	arrival in the roundabout is determined by an infinite flow of PCU and pedestrians
FIFO	–	when coming into the system, PCU and pedestrians are first served according to the first-in-first-out (FIFO) selection rule

The $M/M/1/\infty/FIFO$ system for the traffic flow of PCU and the system for the pedestrian traffic flow are schematically shown in the Figure 2 [10], [11], [12] for the example of the roundabout arm in question.

Figure 2. The individual roundabout arm under the analysis

Because of three independent traffic flows PCU_i ($i = 1, 2, 3$) and the two independent pedestrian flows j ($j = 1, 2$), an individual arm in the roundabout presents a combination of two mutual dependent systems, that is:

- The combination of $M/M/1/\infty/FIFO$ for the PCU_4 main traffic flow and pedestrian j ($j = 1, 2$) flow $M/M/1/\infty/FIFO$.
- The combination of $M/M/1/\infty/FIFO$ for the PCU_3 circulating flow and the PCU_4 main flow $M/M/1/\infty/FIFO$.

While the PCU traffic flow presents a typical $M/M/1/\infty/FIFO$ system, the pedestrian traffic flow system $M/M/1/\infty/FIFO$ is modified, since the waiting time periods and the waiting line never occur. This statement can be explained by the fact that pedestrians in the roundabout are always given priority over the motorised flow. Because of the complexity and non-determination of the system, the capacity of the traffic flow of an individual arm of the roundabout and the entire roundabout is difficult to be analytically treated. A possible solution to the problem is the use of discrete numeric simulations method, which is presented in the following section.

4. SIMULATION MODEL OF THE ROUNDABOUT

According to discrete models [5], [6], [7], [14], [15], [16], [17], [18], [19], [20] and the traffic movement, simulation methods can be generally divided into two groups, (*i*) macroscopic and

(*ii*) microscopic models. Macroscopic models combine vehicles and travelling among groups, the traffic flow is presented as a statistical model; the results are presented as the average value after certain time. With macroscopic models the emphasis is laid on the links, intersections are simplified in the model. Unlike microscopic models, macroscopic models focus on a long-term planning period. With microscopic models every vehicle, pedestrian, cyclist, etc. can be described with real characteristics (dimension, velocities, accelerations, decelerations, etc.). Microscopic models are usually used for traffic flow analyses in a short-term planning period.
Considering the complexity of the analytical model of the roundabout and the application of the discrete simulation technique, a discrete event simulation was used for the analysis of the capacities of the observed area of the roundabout. In our paper, a special program tool AutoMod [8] has been used for the capacity analysis of the roundabout. AutoMod [8] is mostly used to implement discrete numeric simulations of internal logistic systems and all other logistic discrete systems. To the user it offers a reliable tool for planning or reconstructing complex and inter-dependent systems and it has already been put to use in works of our research team [10], [11], [12], [20]. The programming tool consists of individual programming modules that construct the AutoMod [8] as integrity. When modelling a general system, the already built-in elements (connection transporters, automated transport vehicles, etc.) that present certain complexes in the chosen process can be used. In the source file, the characteristics which suit the real situation are determined. With the help of command lines in the source file the implementation of the simulation is determined. On the basis of the acquired results of simulation analysis and its statistical processing in AutoStat [8] , the efficiency of the system is analysed.

4.1 Input data for building-up the simulation model

When building-up the simulation model for a definite area of the one-lane three-armed roundabout, the actual geometry of the roundabout and the velocity characteristics of motorised vehicles and pedestrians (Table 1) were considered. The mean velocity of the PCU before entering the roundabout equals 40 *km/h*, in the area of the roundabout it equals 20 *km/h*; the mean velocity of pedestrians equals 5 *km/h*. The arrivals of pedestrians are based on the multi-channel system in which the pedestrians arrive randomly from both sides with probability density functions $f_{P1}(t)$ and $f_{P2}(t)$. In this way the mathematical model can better illustrate the real conditions. The influence of cyclists is neglected. The influence of the roundabout circulation is taken into account (PCU_3), with the presumed mean velocity 20 *km/h.* For all motorised vehicles (the main traffic flow PCU_4, the circulating flow in the roundabout PCU_3 and the traffic flow from the roundabout in the direction of Koroška Street – East PCU_5), the personal car unit model (PCU) is applied.
Legend according to Figure 3 (MP – measuring point):
MP1 – Arrival of pedestrians 1 with probability density function $f_{p1}(t)$ in the direction to north N
MP2 – Arrival of pedestrians 2 with probability density function $f_{p2}(t)$ in the direction to south S
MP3 – Circulating PCU_3 flow in the roundabout (arrival of PCU_3 is based on probability density function $f_{PCU3}(t)$)
MP4 – Main PCU_4 flow in arm A (arrival of PCU_4 is based on probability density function $f_{PCU4}(t)$)
MP5 – PCU_5 flow from the roundabout in the direction to Koroška Street east E (arrival of PCU_5 is based on probability density function $f_{PCU5}(t)$)

Figure 3. Geometry of the roundabout

Table 1. Geometrical and kinematics input data

Geometrical input data	
Outside diameter of the roundabout	31 m
Inside diameter of the roundabout	19 m
Width of the road	3.7 m
Width of the pedestrian crossing	4.5 m
Length of entrance road of observed area	Arm A – 115 m,
Length of pedestrian crossing	10 m
Kinematics input data	
Velocity $v_{1,2}$ of a pedestrian	5 km/h
Velocity v_3 of a PCU in the roundabout	20 km/h
Velocity v_5 of a PCU near the pedestrian crossing	20 km/h
Velocity v_4 of a PCU on the arm	40 km/h

For the purpose of the simulation model calibration, a three hours counting (6.30 – 9.30) in the morning peak hours of motorised vehicles and pedestrians have been conducted on the roundabout at Koroška street in Maribor. The areas (see Figure 3) where counting was performed are labelled with MPi (i = 1,…,5). Based on the traffic count of motorised vehicles and pedestrians of the roundabout on Koroška Street, the acquired data have been statistically evaluated. The experimentally acquired input data present the input data for the traffic flow of motorised vehicles and pedestrians in the simulation model. Since the measurements were taken using counting on an individual roundabout's arm, the presumption has been made that the traffic flow of PCU_i (i = 1, 2, 3) and pedestrian flow j (j = 1, 2) match with *Poisson's statistical distribution*. In this case the time between the arrivals of two PCU and pedestrians is distributed according to the *exponent statistical distribution*. The frequencies λ_i [Q_i/sec.] and mean time between two arrivals t_i [sec./Q_i] of the traffic of motorised vehicles and pedestrian traffic that are used in this work are presented in Table 2.

Table 2. Frequencies and mean time between two arrivals based on counting in the morning peak Hours (6.30 – 9.30)

Pedestrians i / PCU_i	Capacity Q_i	Frequency λ_i [Q_i/sec.]	Mean time between two arrivals t_i [sec./Q_i]
Pedestrians 1	1120	0.1037	*exp*(9.65)
Pedestrians 2	254	0.02352	*exp*(42.58)
PCU_3	1073	0.09935	*exp*(10.06)
PCU_4	2053	0.19	*exp*(5.26)
PCU_5	1697	0.1571	*exp*(6.37)

4.2 Simulation model of the roundabout

On the basis of the real roundabout in Koroška Street in Maribor the simulation model has been built (Figure 4 presents a draft of the simulation model). The simulation model in the AutoMod [8] is illustrated with paths, on which the motorised vehicle (PCU) and pedestrian traffic flows are entwined. The model derives from the theory of the expected time void in the pedestrian traffic flow, used by vehicles for entering and exiting the roundabout, presuming that pedestrians always have priority. The geometry of the roundabout was copied in the simulation model, whereby all the necessary data are taken into account (see Table 1). For the model calibration with real conditions in practice, the counting of the motorised traffic flow and the pedestrian flow in the analysed arm of the roundabout has been performed in the morning peek hour (see

Table 2). The cyclists are not discussed in this model. The arrivals of motorised vehicles in the roundabout are based on the *Poisson statistical distribution*, whereby the mean value (λ_3) has been obtained on the basis of the conducted counting in the morning peek hour. Additionally, the circular flow of motorised vehicles in the roundabout was considered, which also presents an additional disturbance for the main flow of motorised vehicles on the entry. The pedestrian flows are defined as a multi-channel flow with the *Poisson statistical distribution* with mean values (λ_1 and λ_2), which have been obtained on the basis of the conducted counting in the morning peak hours. In the model restrictions such as: the constant mean velocity of pedestrians $v_{1,2}$ and the constant mean velocity of motorised vehicles $v_{3,4,5}$ without any respect to the driver behaviour, have been considered.

Figure 4. Micro-simulation model of the roundabout [8]

The operation of the simulation model is governed by a program code in the source file according to the following algorithm.

Figure 5. Algorithm of the course of operating the simulation model of the roundabout

The simulation begins with a process based on user determined functions in the source file of the program. The functions in the source file start the operation of the roundabout. When the function »*Begin model initialization function*« equals »true«, the process »*P_roundabout_start*« begins. The process consists of project variables, pedestrians and PCU attributes of type integer and real, subroutines and individual program loops.

4.2.1 The gap acceptance model

The gap acceptance model of the roundabout has been modelled using the »*Block claim and Block release functions*« and the »*Order list*«. The »*Block claim function*« for the arrival of PCU_4 on the considered pedestrian crossing verifies whether there is already a pedestrian on the pedestrian crossing or not. If there is a pedestrian on the pedestrian crossing (the function »*B_block_1 current claims* <> *0*«), the PCU_4 immediately stops and waits until the pedestrian leaves the pedestrian crossing. During the waiting period, the PCU_4 is inscribed into the *order list wait for path* (»*wait to be ordered on Ol_waitForPath_1*«). When the pedestrian flow is extremely heavy, waiting lines of PCU_4 occur. The moment the pedestrian crossing is free the »*B_block_1 current claims = 0*«, PCU_4 continues with driving in the first-in-first-out (FIFO) consequence according to their waiting line. The driving of PCU_4 takes place until the next pedestrian appears on the pedestrian crossing, which again stops the driving of PCU_4. The proposed model deals with the multi-channel system in which the pedestrians arrive randomly from both sides (north and south) of the pedestrian crossing. There are 6 possible channels for the pedestrians 1 who are travelling towards north and 6 possible channels for the pedestrians 2 who are travelling towards south. Because of each channel m (m = 1,…,6) has the equal probability to be selected for the pedestrian the uniform discrete distribution has been used.
The probability scheme equals:

$$X : \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6 \end{pmatrix} \quad (1)$$

The probability function equals:

$$
\begin{aligned}
&p_x(x_i) = p_i \quad i = (1,....,6) \\
&0 \le p_i \le 1 \\
&p_1 + p_2 + ... + p_m = 1 \\
&1/6 + 1/6 + 1/6 + 1/6 + 1/6 + 1/6 = 1
\end{aligned} \tag{2}
$$

In this way the mathematical model can illustrate the real conditions better. In the case of roundabout circulating flow PCU_3 and the main traffic flow PCU_4, the same approach with the »*Block claim and Block release functions*« and the »*Order list*« has been used. For every passing of PCU_4 and pedestrians the program registers the basic information variables »*V_waiting_time*« for PCU_4, »*V_no._of_ PCU₄*« and »*V_no._of_pedestrians*« as follows: the number of passing PCU_4 and the number of pedestrian crossings at the roundabout, the period an individual PCU_4 has been in the observed arm of the roundabout (the waiting time period) and the number of successfully passed PCU_4 and pedestrians in the defined time. The main goal of the simulation analysis is to establish the PCU_4 capacity on the observed arm when the waiting line in front of the pedestrian crossing and consequently the waiting time for crossing the observed arm is still acceptable.

5. ANALYSIS OF THE RESULTS

The results of the performed analysis for determining the mean waiting time and the mean capacity of the PCU_4 main traffic flow depending on the pedestrian flows give basic conclusions, presented in Tables 3, 4 and 5.

With regard to the performed counting of the traffic flow of motorised vehicles and pedestrian flow (see Table 2) it can be stated that the frequency of pedestrians 1 (λ_1) presents the biggest influence on the capacity of the PCU_4 main traffic flow. Assuming that the pedestrian frequency will only get bigger in the future (closure of the old bridge, increase in the public transportation), it is necessary to find out what level of increase in the number of pedestrians in both directions with regard to the main traffic flow of PCU_4 would still be admissible. When analysing the capacity of the treated arm of the roundabout, we deal with a number of independent variables, i.e. different frequencies of the motorised vehicle traffic flow (λ_3, λ_4, λ_5) and pedestrian flow (λ_1, λ_2). To determine the influence of a variable on the system's response (waiting time and roundabout capacity) it is therefore necessary to fix individual variables and change the value of only one variable or two variables at the same time. Since we are mainly interested in the influence of pedestrians on the capacity of the selected roundabout arm, the frequency of pedestrians 1 (λ_1) and the frequency of pedestrians (λ_2) in the roundabout arm present the main variables. Due to a different frequency of pedestrians in both directions (λ_1 = 0.1037 ped/sec. and λ_2 = 0.02352 ped/sec.) the influences on the waiting time and capacity of the roundabout for PCU_4 have been analysed in the following way:

a) beside the fixed variables (λ_3 = 0.09935, λ_4 = 0.19, λ_5 = 0.1571) the frequency of pedestrians 2 (λ_2 = 0.02352) has been fixed. In the analysis, values λ_1 have been increased to the level that the mean waiting time and mean capacity of the main traffic flow of PCU_4 are still admissible (see Table 3);
b) beside the fixed variables (λ_3 = 0.09935, λ_4 = 0.19, λ_5 = 0.1571) the frequency of pedestrians 1 (λ_1 = 0.1037) has been fixed. In the analysis, values λ_2 have been increased to the same level as the frequency of pedestrians 1 (see Table 4);
c) the variables (λ_3 = 0.09935, λ_4 = 0.19, λ_5 = 0.1571) have been fixed. In the analysis, values of frequency λ_1 and λ_2 have been increased to the level that the mean waiting time and mean capacity of the main traffic flow of PCU_4 are still admissible (see Table 5).

Analysis results for every mean waiting time and the roundabout capacity shown in Tables 3, 4 and 5 have been carried out on the basis of 100 consecutively performed simulations in the AutoStat programming tool [8]. Consequently, a good enough representative average is obtained, which would not be in the case of probability functions with a small number of performed simulations.

Table 3. The influence of increasing arrivals of pedestrians 1 on the mean waiting time and mean capacity for the main traffic flow of PCU_4

λ_2, λ_3, λ_4 λ_5 are const.	Arrivals of pedestrians 1				
	Pedestrians 1 ($1/\lambda_1$ = 9,65)	Pedestrians 1 ($1/\lambda_1$ = 7,72)	Pedestrians 1 ($1/\lambda_1$ = 5,79)	Pedestrians 1 ($1/\lambda_1$ = 3,86)	Pedestrians 1 ($1/\lambda_1$ = 2,895)
Mean wait. time T (sec.)	3.62	4.49	6.81	18.58	266.67
SD	0.25	0.34	0.74	3.06	117.92
Confidence (95 %)	(3.58 – 3.67)	(4.27 – 4.56)	(6.67 – 6.96)	(17.97 – 19.18)	(243.27 – 290.06)
Mean cap. Q_4 (PCU's$_4$)	2048	2048	2048	2046	1956
SD	48	48	48	47	35
Confidence (95 %)	(2039 – 2058)	(2039 – 2058)	(2039 – 2058)	(2037 – 2056)	(1949 – 1963)

Table 4. The influence of increasing arrivals of pedestrians 2 on the mean waiting time and mean capacity for the main traffic flow of PCU_4

λ_1, λ_3, λ_4 λ_5 are const.	Arrivals of pedestrians 2				
	Pedestrians 2 ($1/\lambda_2$ = 42,58)	Pedestrians 2 ($1/\lambda_2$ = 34,064)	Pedestrians 2 ($1/\lambda_2$ = 25,548)	Pedestrians 2 ($1/\lambda_2$ = 17,032)	Pedestrians 2 ($1/\lambda_2$ = 12,774)
Mean wait. time T (sec.)	3.62	3.8	4.15	4.94	5.87
SD	0.25	0.28	0.33	0.46	0.6
Confidence (95 %)	(3.58 – 3.67)	(3.75 – 3.86)	(4.09 – 4.21)	(4.85 – 5.03)	(5.76 – 5.99)
Mean cap. Q_4 (PCU's$_4$)	2048	2048	2048	2048	2048
SD	48	48	48	48	48
Confidence (95 %)	(2039 – 2058)	(2039 – 2058)	(2039 – 2058)	(2039 – 2058)	(2039 – 2058)

Table 5. The influence of increasing arrivals of pedestrians 1 and pedestrians 2 on the mean waiting time and mean capacity for the main traffic flow of PCU_4

λ_3, λ_4 λ_5 are const.	Arrivals of pedestrians 1 and pedestrians 2				
	Pedestrians 1 ($1/\lambda_1$ = 9,65) Pedestrians 2 ($1/\lambda_2$ = 42,58)	Pedestrians 1 ($1/\lambda_1$ = 7,72) Pedestrians 2 ($1/\lambda_2$ = 34,064)	Pedestrians 1 ($1/\lambda_1$ = 5,79) Pedestrians 2 ($1/\lambda_2$ = 25,548)	Pedestrians 1 ($1/\lambda_1$ = 3,86) Pedestrians 2 ($1/\lambda_2$ = 17,032)	Pedestrians 1 ($1/\lambda_1$ = 2,895) Pedestrians 2 ($1/\lambda_2$ = 12,774)
Mean wait. time T (sec.)	3.62	4.76	7.83	36.92	929.52
SD	0.25	0.38	1.0	10.15	165.05
Confidence (95 %)	(3.58 – 3.67)	(4.68 – 4.83)	(7.63 – 8.03)	(34.91 – 38.94)	(896.77 – 962.27)
Mean cap. Q_4 (PCU's$_4$)	2048	2048	2048	2043	1694
SD	48	48	48	47	37
Confidence (95 %)	(2039 – 2058)	(2039 – 2058)	(2038 – 2057)	(2033 – 2052)	(1687 – 1701)

In the case of fixing the values of the variables for the traffic flow (λ_3, λ_4, λ_5) and the pedestrian flow 2 (λ_2) it can be noticed that the pedestrian flow 1 in the direction of "Nord" towards "South" (see Figure 3) has a major influence on the mean waiting time of the main traffic flow of PCU_4. When increasing the frequency λ_1 from 20 % to 40 % one can notice a rather small increase in the mean waiting time, whereby the PCU_4 capacity remains the same all the time. For this purpose the frequency of pedestrians 1 was increased for 60 % and it has been found out that the mean waiting time has enormously increased in comparison with the previous increases of frequency, whereby the capacity of PCU_4 remains unchanged. It has been determined that with constant – linear increase of the frequency λ_1 the mean waiting time of PCU_4 does not increase evenly. In the continuation of analysis, the frequency λ_1 was increased from 60 % to 70 %. We have established that the mean waiting time of PCU_4 has increased to 266.67 seconds, which is unacceptable for the traffic flow in the roundabout. On the basis of results in Table 3 it can be concluded that theoretically there is a 60 % reserve of the capacity in the case of increase of pedestrian 1 frequency. This statement is valid under the condition that the frequencies of traffic flow (λ_3, λ_4, λ_5) of PCU are fixed and unchangeable. The same holds true for the frequency (λ_2) of the pedestrian flow 2.

In the continuation of the analysis, when operating with the pedestrian flow 2, the influence of increasing the frequency λ_2 on the mean waiting time of the main traffic flow of PCU_4 was compared. Due to the simultaneous treatment with several variables the values of variables (λ_1, λ_3, λ_4, λ_5) were fixed. In Table 4 it can be observed that the increase of the pedestrian frequency 2 does not have a major influence on the mean waiting time and capacity of the main traffic flow of PCU_4. This finding is reasonable since the pedestrian frequency 2 (λ_2 = 0.02352 ped./sec) is relatively small considering the pedestrian frequency 1 (λ_1 = 0.1037 ped./sec) and consequently has a smaller influence on the mean waiting time of PCU_4. This means that theoretically there is a relatively great reserve of capacity in the case of the increase of pedestrian frequency 2.

The actual roundabout capacity is definitely dependent on the simultaneous consideration of pedestrian frequencies 1 and 2 as well as on other fixed variables (λ_3, λ_4, λ_5) of PCU. For this reason Table 5 shows dependencies of the mean waiting time and PCU_4 capacity with a simultaneous increase of pedestrian frequencies (λ_1, λ_2) for pedestrians 1 and pedestrians 2. Because of the simultaneous influence of both pedestrian flows 1 and 2, the mean waiting time is higher than in previous cases. The dependency of the mean waiting time and capacity of the main traffic flow PCU_4 is similar to the dependency in the case of only increasing the pedestrian frequency λ_1 and fixed values of other variables (λ_2, λ_3, λ_4, λ_5). Due to a relatively small influence of pedestrians 2 and a great influence of pedestrians 1 there is a theoretical 60 % reserve of capacity at a simultaneous increase of pedestrian frequencies λ_1 and λ_2.

6. CONCLUSION

In this paper the determination of the actual throughput capacity of the roundabout's arm by using the micro-simulation and discrete functions is presented. The analysis presented in this paper provides an approach with the simultaneous use of the main and the circulating flow and the influence of the strong pedestrian flow by using the multi-channel system. Because of the highly complex influence of motorized vehicles flow and multi-channel pedestrians flow the mathematical modelling of traffic flows with the use of discrete simulations has been used for the analysis.

The main part of our paper deals with the discrete numeric simulation of the roundabout. The simulation model of the roundabout is general, therefore it can be extended for every individual implementation according to the chosen geometrical and kinematics sizes. The mathematical model derives from legalities of acceptable time voids in the pedestrian traffic flow, used by the vehicles for entering/exiting a roundabout, using the *exponent* and *Poisson statistical distribution*. For determination of the traffic flow of motorised vehicles and pedestrians the real input data acquired by the traffic counting at Koroška Street Maribor in the morning peak hours have been used. The results (the mean capacity of PCU_4) acquired with measurements of the traffic flow and simulation analyses match well, which means that simulation analysis results give a good prediction for the evaluation of the mean waiting time and waiting lines of motorized vehicles in the analysed arm of a roundabout. It has been determined that the current situation of the traffic flow is acceptable for the roundabout capacity. With an increase of the pedestrian flow (in both directions) a major influence on the roundabout capacity is not expected. On the basis of analysis results it can be established that there is a relatively high reserve available – up till 60 % of current frequencies λ_1 in λ_2. Since the traffic flow of PCU_i is going to increase in the future, we assume that the capacity reserve will get lower, but it will still be high enough to allow an undisturbed traffic flow of PCU_i.

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POVZETEK

DOLOČANJE DEJANSKE PROPUSTNE SPOSOBNOSTI KRAKA KROŽNEGA KROŽIŠČA Z UPORABO MIKROSIMULACIJE IN DISKRETNIH FUNKCIJ

Prispevek prikazuje vpliv večkanalnega toka pešcev na dejansko propustno sposobnost eno-pasovnega krožnega križišča z uporabo mikro-simulacij in diskretnih funkcij. Predlagani model temelji na teoriji pričakovane časovne praznine med enotami prometnega toka pešcev, ki imajo pri prečkanju kraka krožnega križišča prednost pred motornimi vozili. Predlagani model predstavlja nadgradnjo predhodnih raziskav na področju modeliranja prometnih tokov v eno-pasovem krožnem križišču. Poleg večkanalnega toka pešcev so hkrati upoštevane tudi motnje zaradi krožečega toka motornih vozil v križišču. S tem je doseženo, da model še bolje ponazarja realno dogajanje v prometu. Simulacijska analiza je bila izvedena na krožnem križišču, ki se nahaja na Koroški ulici v Mariboru. Rezultati analize so pokazali sorazmerno visoko propustno sposobnost glavnega prometnega toka motornih vozil v analiziranem kraku križišča. Predstavljeni model predstavlja uporabno in prilagodljivo orodje za načrtovanje kapacitete križišč v praksi in analizo vpliva posameznih spremenljivk na propustno sposobnost križišča.

KLJUČNE BESEDE

križišča, analiza prometnega toka, mikro-simulacijsko modeliranje, analiza propustne sposobnosti

FIGURES

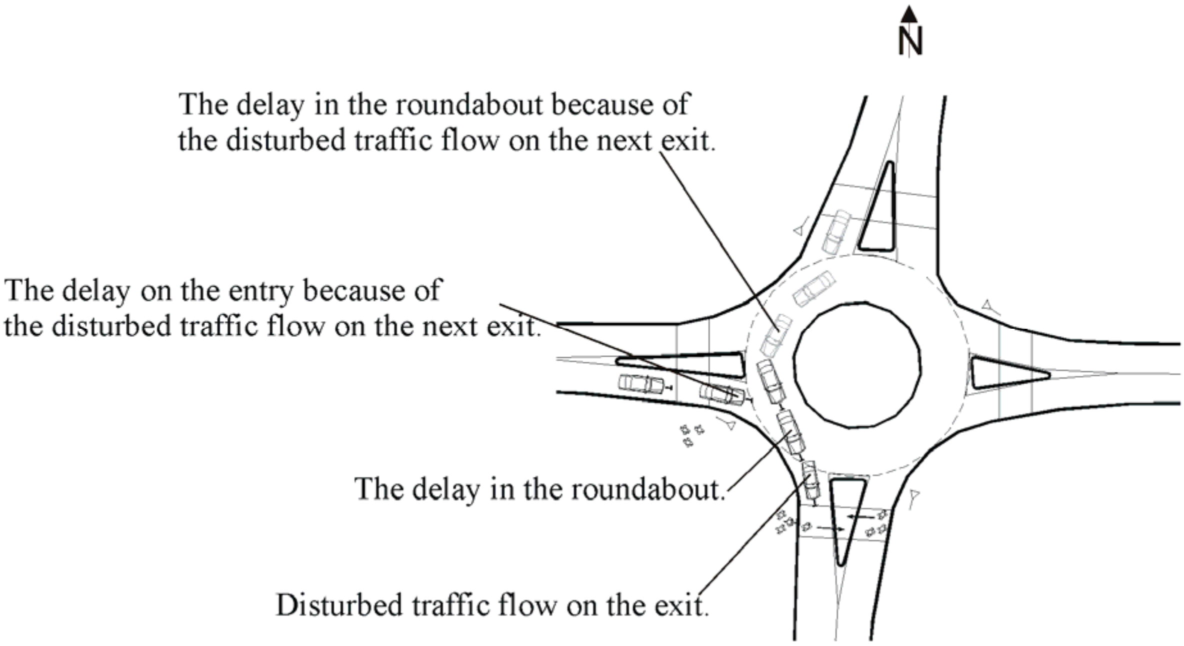

Figure 1. Queue formation at a roundabout [9]

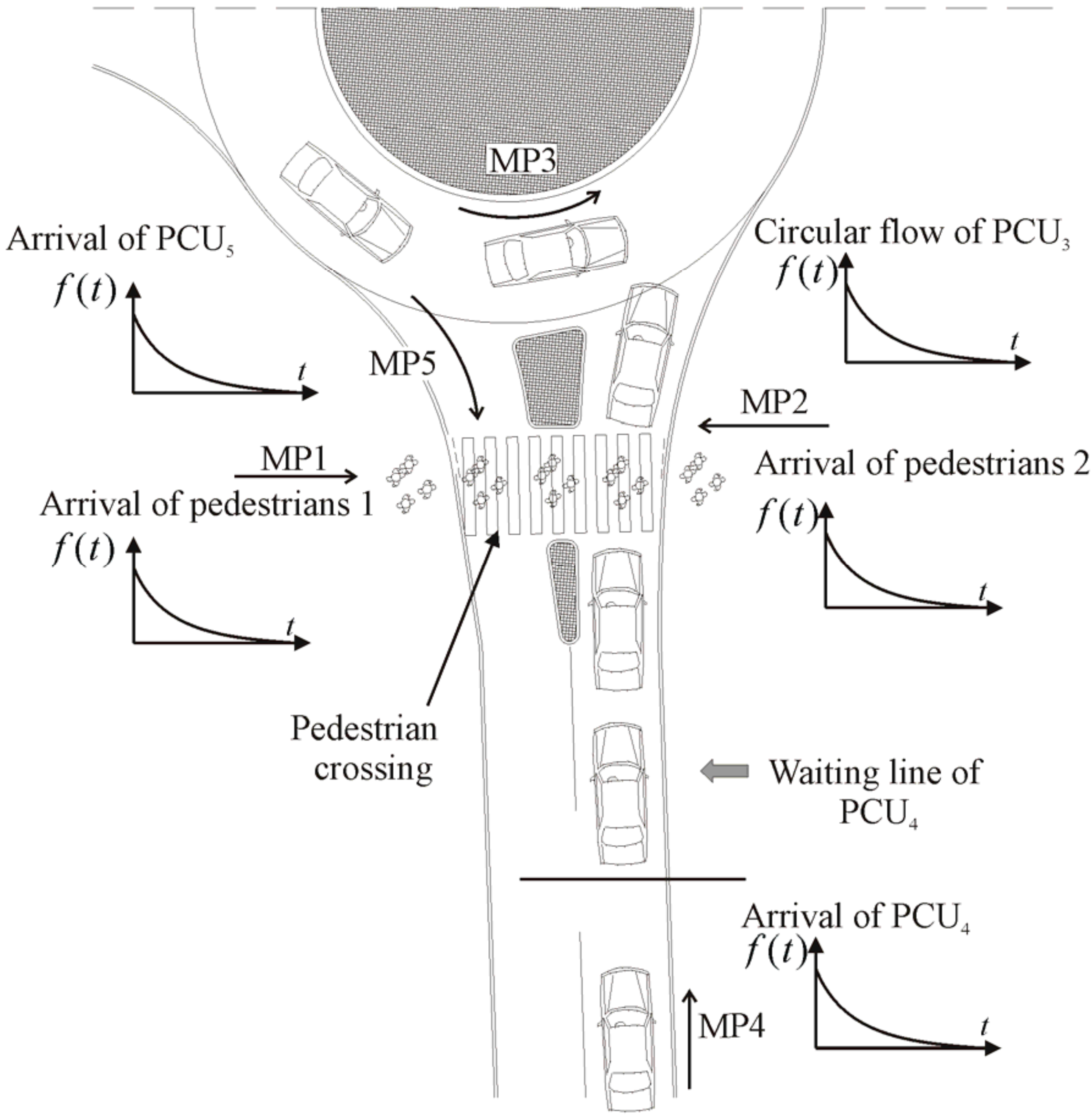

Figure 2. The individual roundabout arm under the analysis

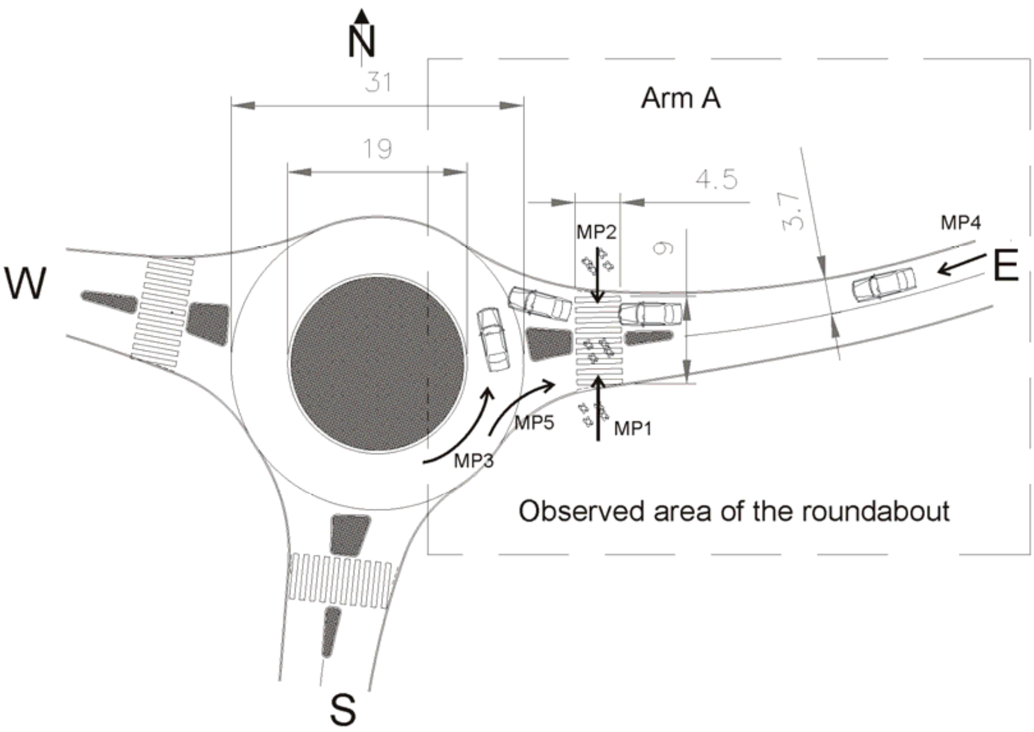

Figure 3. Geometry of the roundabout

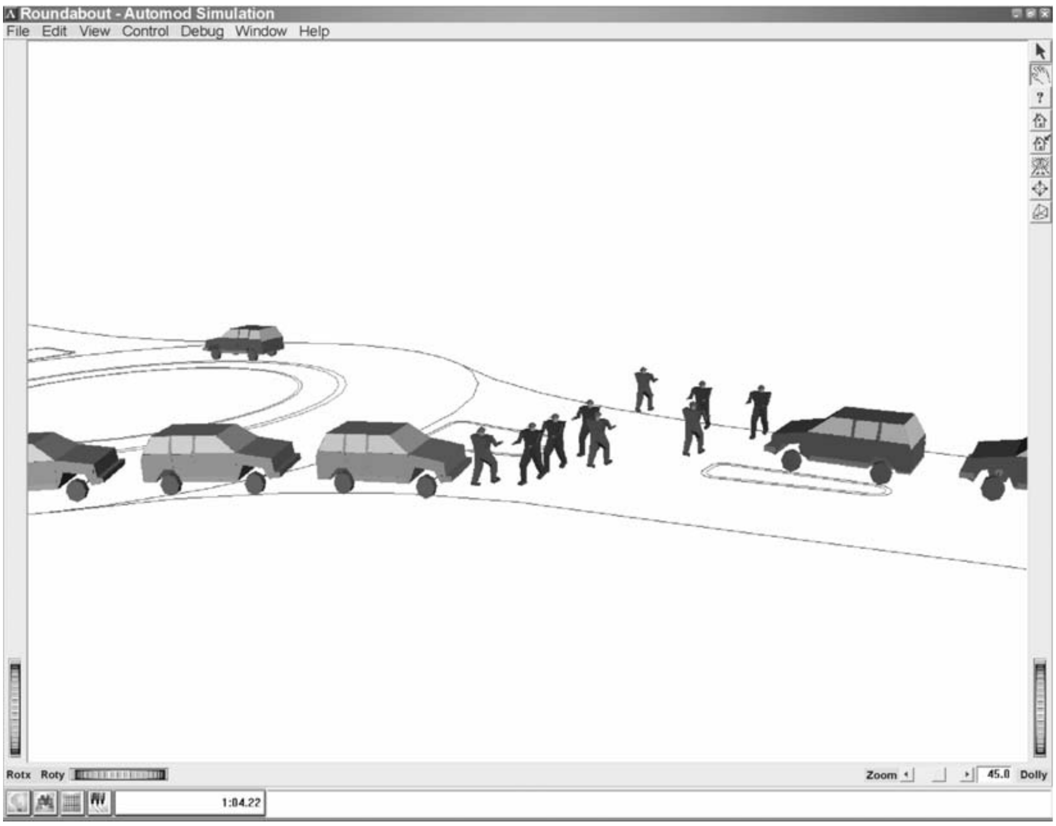

Figure 4. Micro-simulation model of the roundabout [8]

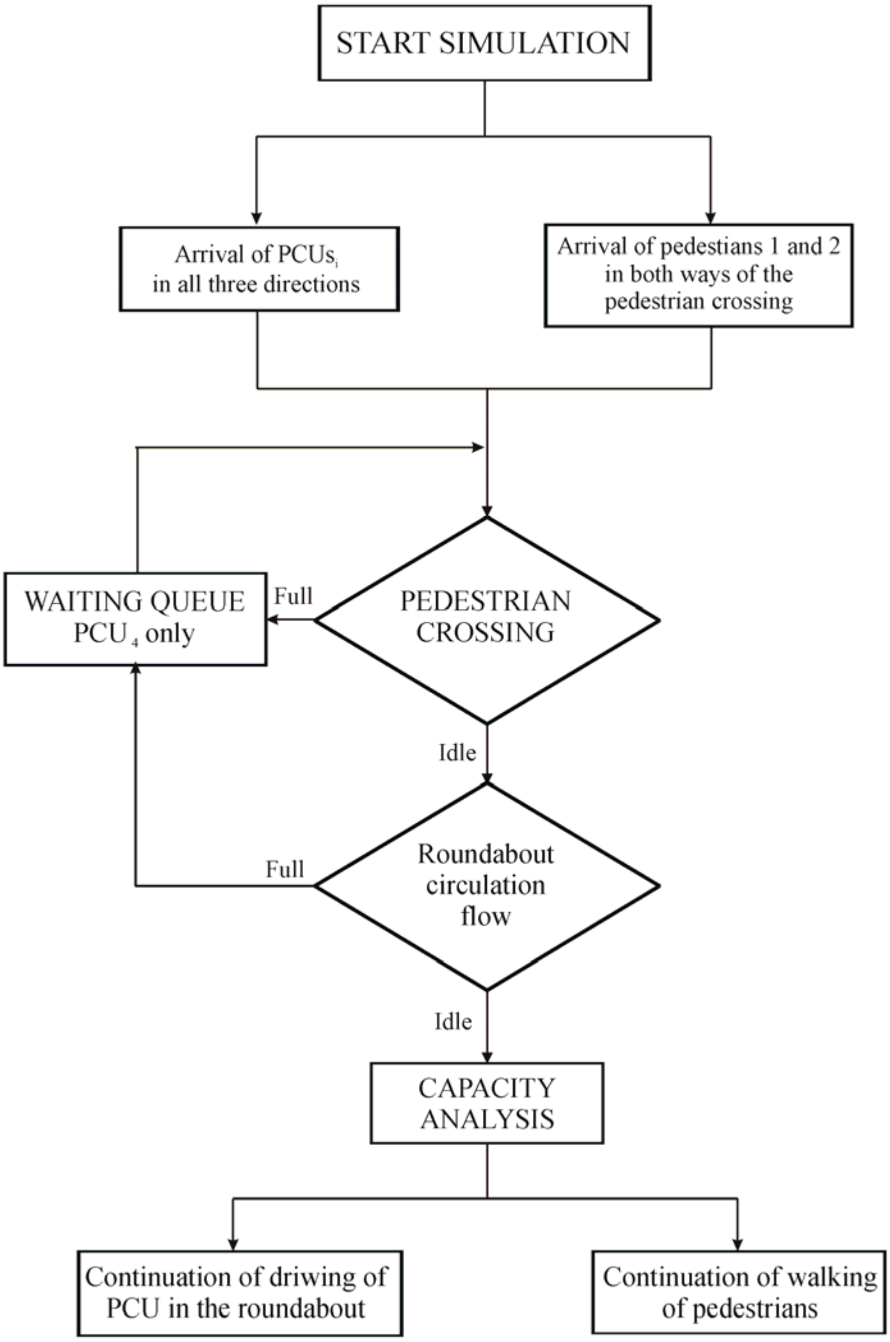

Figure 5. Algorithm of the course of operating the simulation model of the roundabout