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The Use of Micro-Simulation in Determining the Capacity of a Roundabout with a Multi-Channel Pedestrian Flow

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The main purpose of this paper is to analyse the influence of the multi-channel pedestrian flow on the capacity of the one-lane roundabout, using discrete simulation methods. 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. 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 in the morning peek hour. The results of the analysis have indicated a high reserve of the capacity for pedestrians who arrive from the left and right sides of the roundabout with regard to motorised vehicles in the analysed arm of the roundabout. The real reserve of the capacity would otherwise be smaller in case of enlargement of the motorised vehicle flow in the future. Nevertheless it would be high enough for an undisturbed traffic flow of motorised vehicles through the roundabout to be possible. The presented methodology 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.

Keywords: roundabout, pedestrian flow, traffic flow modeling, simulation models

0 INTRODUCTION

In one-lane roundabouts difficulties with the throughout capacity of the roundabout can occur due to a strong pedestrian traffic flow. Vehicles on entries and exits should as a rule give priority to pedestrians. Due to this fact disturbances occur in the main vehicle flow [1] to [3].

The possibility of a blockage of the roundabout can be determined in several ways. In the past, authors [4] and [5] have used different ways of determining the capacity of roundabouts and different approaches of determining the influence of the non-motorised flow on the capacity of a roundabout. The common features of all these approaches are mathematical models and a definite simplification for the calculation of the roundabout capacity [6]. Among simple methods where only a diagram or one equation is used are the German method for determining the pedestrian influence [7] and the Dutch method for determining the cyclist influence [8] on the throughout capacity of the one-lane roundabout.

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. 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

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models. Several analytical and micro-simulation models offer variants of the roundabout analysis based on either the gap acceptance or empirical approaches. Examples of such codes are RODEL [9], PARAMICS, VISSIM, SYNCHRO [9], SIDRA [10] to [12], etc. For the presented problem the computer tool AutoMod [13] 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 of traffic flows. The proposed 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. 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 (Fig. 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 we also consider definite 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. The main purpose of this paper is to analyse the influence of the pedestrian flow and consequently the capacity of the one-lane three-armed roundabout, using the discreet numeric simulation modelling.

1 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 the traffic still flows normally. In the second case, the influence of the pedestrian flow is so large that bottlenecks on the roundabout entry and exit are possible, which then influences the queues upon the adjacent roundabout arms [3]. If the vehicle queue is so long that it reaches the previous entry, problems with the occupation of the roundabout arise and a blockage of the entire roundabout can occur. In reality, the abovementioned problems of entering and exiting a roundabout normally appear simultaneously. It is also common 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

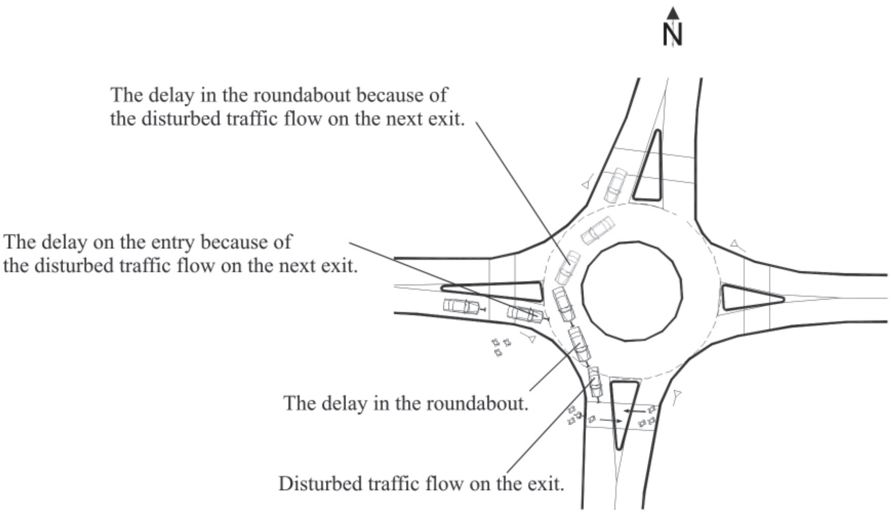

Fig. 1. *Queue formation in a roundabout [3]*

cases the blockage of the roundabout is easier to occur. In the following paragraph, an example of the roundabout where a 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 (Fig. 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.

In the one-lane roundabout with the waiting space for one vehicle only the following three situations can generally occur in the waiting place between the pedestrian crossing and the outer edge of the circulatory roadway:

- 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 line 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 the pedestrian 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 throughput capacity and the efficiency 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 discreet simulations of the traffic flows of motorised vehicles, pedestrians and/or cyclists. In the following chapter the basic theoretical background for the analysis of the traffic flow in the roundabout is given. The simulation model and the simulation analysis of real and variable data which are presumed to be the case in the future (the enlargement of the motorised vehicle and pedestrian flows) are given.

2 THE SIMULATION OF THE TRAFFIC FLOW IN THE ROUNDABOUT

The analysis of the traffic flow using discreet event simulations presents a successful way of analysing complex intersections for determining capacity, as presented in [10] to [16]. According to discreet models and traffic movement, simulation methods can be generally divided into two groups, (*i*) macroscopic and (*ii*) microscopic models. With macroscopic models the emphasis is laid on the traffic flows. 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.).

Considering the complexity of the analytical model of the roundabout and the application of the discreet simulation technique, the discreet event simulation was used for the analysis of the flow capacity of the observed area of the roundabout. In this contribution, the program tool AutoMod [13] has been used for the capacity analysis of the roundabout. AutoMod is mostly used to implement discreet numeric simulations of internal logistic systems and all other logistic discreet systems [1] and [17]. The programming tool consists of individual programming modules that construct the AutoMod as integrity. When modelling a general system, the already built-in elements (continuous transporters, automated transport vehicles, etc.) that present certain complexes in the chosen process can be used. 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 the simulation analysis and its statistical processing in AutoStat [13], the success and the efficiency of the system are analysed.

In the following section the steps of the simulation and the analysis of the traffic flow of the motorised vehicles in the three-armed, one-lane roundabout with a strong pedestrian flow on Koroška Street in Maribor (Fig. 2) are shown. Actual geometrical and kinematics data are acquired from a sample of pedestrian and motorised vehicle traffic flows on the observed area of the roundabout, established by counting traffic and statistically evaluating the acquired data (Table 2).

2.1 Input Data for Building the Simulation Model – An Analysis of the Actual Situation of the Traffic Flow Performed by Counting Pedestrians and Vehicles

When building the simulation model for a definite area of the one-lane three-armed roundabout (Fig. 2), the actual geometry of the roundabout and the velocity characteristics of motorised vehicles and pedestrians (Table 1) were considered. The measured data was used for the calibration of the simulation model. The counting – the areas where counting was performed are labelled with MP_i (Fig. 2) and are presented in Table 2. The mean velocity of the Personal Car Unit (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 from both sides with probability density functions $f_{P1}(t)$ and $f_{P2}(t)$ (Fig. 2). The influence of cyclists is neglected. The influence of the roundabout circulation is taken into account (MP_3), with the presumed mean velocity 20 *km/h.* For all motorised vehicles (the main traffic flow MP_4, the circulating flow in the roundabout MP_3 and the traffic flow from the roundabout in the direction of Koroška Street – East MP_5), the personal car unit model (PCU) is applied.

A three-hour (6.30 to 9.30 AM) counting has been performed on the observed area for the requirements of the analysis, separately for the traffic flow of the motorised vehicles and pedestrian traffic. Based on the traffic count of motorised vehicles and pedestrians of the roundabout on Koroška Street, the acquired data have been statistically evaluated. The results of the statistical evaluation of the traffic of motorised vehicles and pedestrian traffic that are used in this work are presented in Table 2. The data in table 2 refers to the period from 6.30 to 9.30 AM.

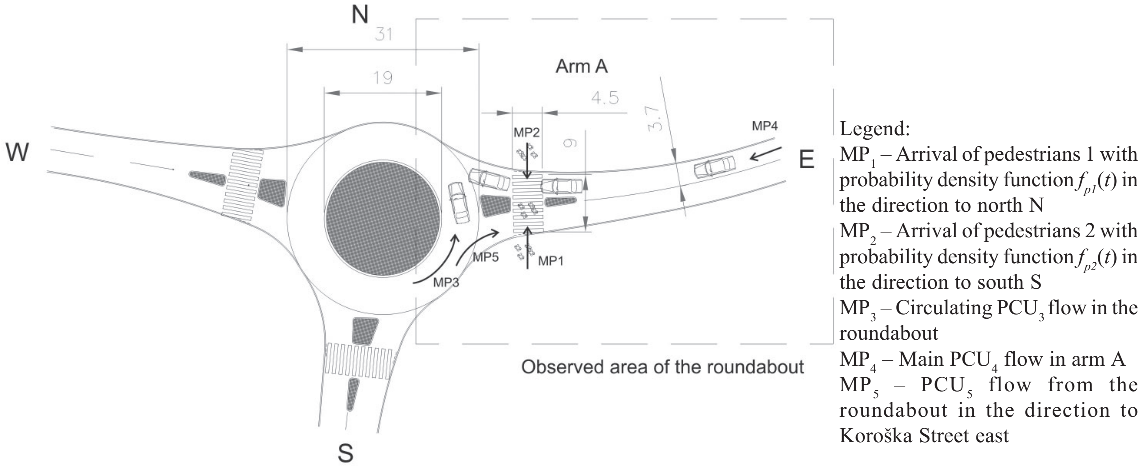

Fig. 2. *Geometry of the roundabout (distances are measured in meters)*

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

Table 2. *Counting of PCU and pedestrians i for the time interval of 3 hours at MP_i*

Time interval AM	Observed area of roundabout				
	MP_1 Pedestrians 1 (Q_1)	MP_2 Pedestrians 2 (Q_2)	MP_3 PCU's 3 (Q_3)	MP_4 PCU's 4 (Q_4)	MP_5 PCU's 5 (Q_5)
6.30 to 6.35	27	2	27	48	43
6.35 to 6.40	18	8	29	60	49
6.40 to 6.45	21	6	27	50	48
6.45 to 6.50	30	10	28	63	53
6.50 to 6.55	64	4	33	70	52
6.55 to 7.00	26	5	44	61	48
7.00 to 7.05	22	4	38	64	50
7.05 to 7.10	24	4	38	57	60
7.10 to 7.15	43	6	37	64	38
7.15 to 7.20	20	5	28	52	41
7.20 to 7.25	39	8	31	55	41
7.25 to 7.30	42	7	34	48	45
7.30 to 7.35	39	10	30	60	53
7.35 to 7.40	61	5	26	67	48
7.40 to 7.45	38	7	45	58	46
7.45 to 7.50	45	9	40	59	53
7.50 to 7.55	36	5	39	64	51
7.55 to 8.00	41	7	34	63	53
8.00 to 8.05	21	7	38	56	50
8.05 to 8.10	35	8	32	58	44
8.10 to 8.15	26	7	32	55	48
8.15 to 8.20	37	5	26	57	43
8.20 to 8.25	22	8	33	61	43
8.25 to 8.30	27	3	23	50	42
8.30 to 8.35	23	6	29	53	49
8.35 to 8.40	25	9	24	52	41
8.40 to 8.45	44	5	27	54	51
8.45 to 8.50	24	8	26	58	47
8.50 to 8.55	29	13	18	53	48
8.55 to 9.00	25	7	23	53	50
9.00 to 9.05	20	9	25	60	56
9.05 to 9.10	22	11	20	48	42
9.10 to 9.15	25	9	22	53	41
9.15 to 9.20	29	9	20	63	47
9.20 to 9.25	24	6	29	58	43
9.25 to 9.30	23	11	21	49	44
SUM	1120	254	1073	2053	1697
Frequency λ_i [Q_i/sec.]	$\lambda_1 = 0.1037$	$\lambda_2 = 0.02352$	$\lambda_3 = 0.09935$	$\lambda_4 = 0.19$	$\lambda_5 = 0.1571$
Mean time between two arrivals *exp*. ($1/\lambda_i$) [sec./Q_i]	*exp*. (9.65)	*exp*. (42.58)	*exp*. (10.06)	*exp*. (5.26)	*exp*. (6.37)

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 arm of the roundabout, the presumption has been made that the traffic flow of PCU_i 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 time between two arrivals of pedestrians or PCU is defined according to the relation presented in the next case. *Case:* the number of PCU_3 arrivals within the time interval from 6.30 to 6.35 is 27, which is presumed to be distributed according to *Poisson statistical distribution*, with an average degree of arrivals per time unit $\lambda = 27/5 = 5,4$ [PCU_3/min]; the time between two consecutive arrivals of PCU_3 can then be determined by using the *exponential statistical distribution* with the mean value of $t = 1/\lambda = 0,185$ [min/ PCU_3].

2.2 The Theoretical Background of the Simulation Model

When planning a roundabout, its capacity in relation to the traffic flow (*i*) of 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 PCU traffic flow. When determining the capacity of a roundabout, the rates of PCU (λ_3, λ_4, λ_5) and pedestrian flows (λ_1, λ_1), crossing each other on an individual arm of the roundabout, are used. The total capacity of PCU 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 system of a waiting queue with one serving place. When determining the appropriate system of the waiting queue, 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

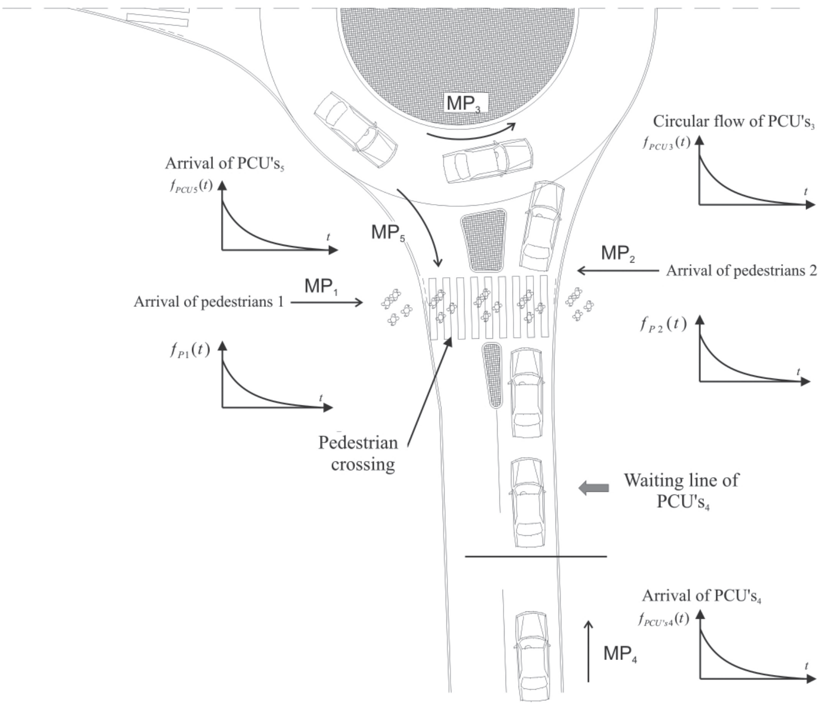

Fig. 3. *An individual roundabout arm (for the observed area see Figure 2)*

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/∞/*FIFO* system for the traffic flow of PCU and the system for the pedestrian traffic flow are schematically shown in the Figure 3 for the example of the roundabout arm in question.

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

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

While the PCU traffic flow presents a typical *M*/*M*/1/∞/*FIFO* system, the pedestrian traffic flow system *M*/*M*/1/∞/*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 impossible to be analytically treated. A possible solution to the problem is the use of discreet numeric simulations method, which is presented in the following section.

2.3 Simulation Model of the Roundabout

On the basis of the real roundabout in Koroška Street in Maribor the simulation model has been created (Figure 4 presents a detailed draft of the simulation model). The simulation model in the programming tool AutoMod [13] is illustrated with paths, on which the motorised vehicle (PCU) and pedestrian traffic flows are entwined. The simulation model has been created on the basis of real geometrical data presented in the CAD drawing and kinematics values, which are presented in Table 1, as well as from a sample of PCU and pedestrian traffic flows (Table 2). The operation of the simulation model is governed by a program code in the source file according to the following algorithm (Fig. 5).

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«,

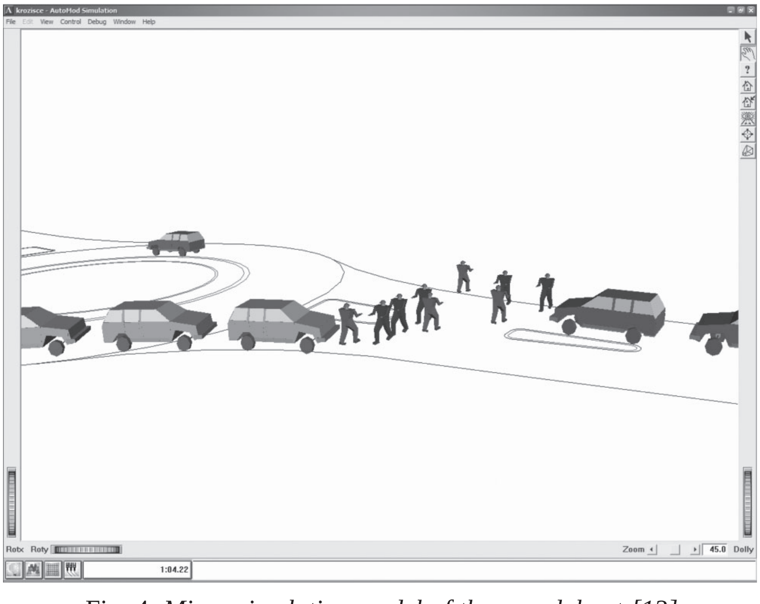

Fig. 4. *Micro-simulation model of the roundabout [13]*

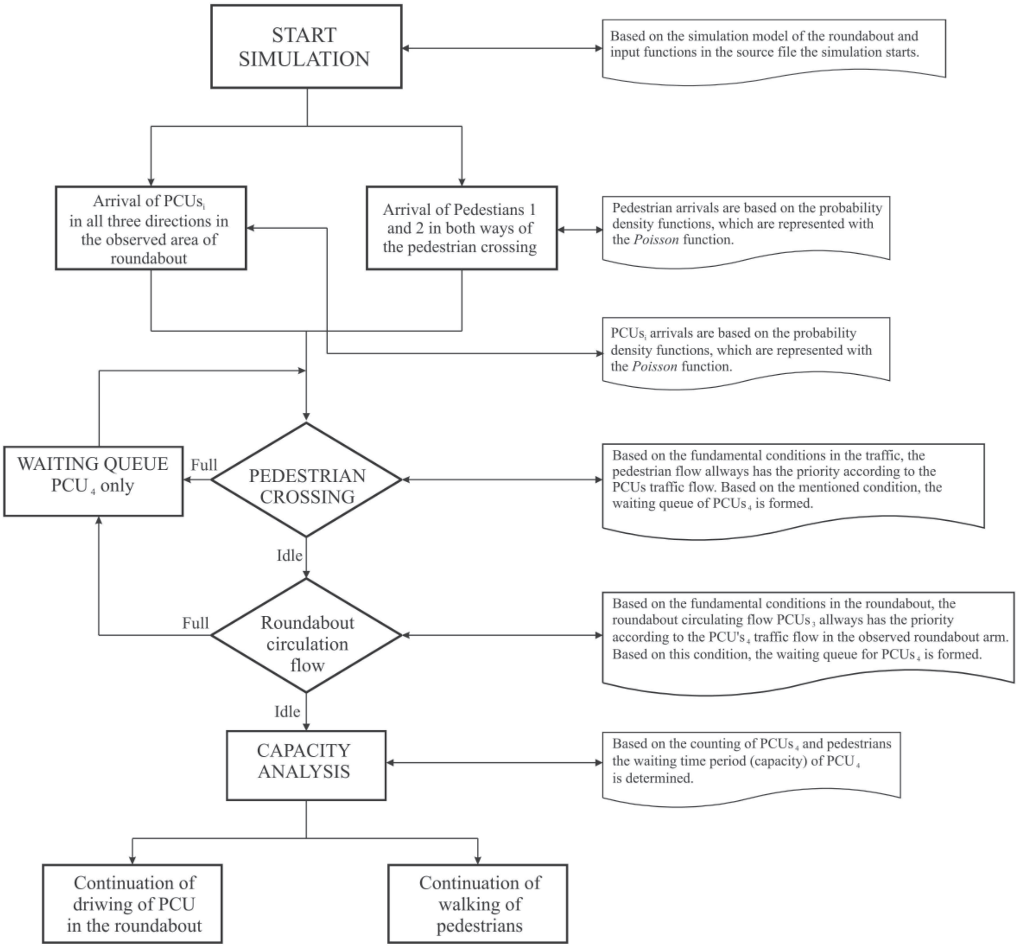

Fig. 5. *Algorithm of the course of operating the simulation model of the roundabout*

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. The model is built according to the defined geometrics construction of the roundabout from the CAD file and kinematics characteristics for pedestrians and PCU. The mean time between two consecutive arrivals of PCU and pedestrians is programmed according to the experimentally acquired values, presented in Table 2. It is presumed that the arrivals of PCU and pedestrians are uneven; therefore the *Poisson statistical distribution* has been used for generating the traffic flow.

• **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 queues 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 queue. The driving of PCU_4 takes place until the next pedestrian appears on the pedestrian crossing, which again stops the driving of PCU_4. 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_ PCU*$_4$« and »*V_no._of_ pedestrians*« as follows: the number of passing PCU_4 and the number of pedestrian crossings in 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 queue in front of the pedestrian crossing and consequently the waiting time for crossing the observed arm is still acceptable.

2.4 Analysis of Results

The results of the performed analysis for determining the mean waiting time and the 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 (Table 2) it can be stated that the frequency of pedestrians (λ_1) presents the biggest influence on the capacity of the PCU_4 main traffic flow (Fig. 4). 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 both variables at the same time. Since we are mainly interested in the influence of pedestrians on the capacity of the 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, λ_4, λ_5) the frequency of pedestrians 2 (λ_2) has been fixed. In the analysis, values λ_1 have been changed or increased to the level that the mean waiting time

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

PCUs arrivals ($1/\lambda_3 = 10.06$) ($1/\lambda_4 = 5.26$) ($1/\lambda_5 = 6.36$)	Arrivals of pedestrians 1 (sec./pedestrian)				
	Pedestrians 1 ($1/\lambda_1 = 9.65$) $\lambda_1 = 100$ % Pedestrians 2 ($1/\lambda_2 = 42.58$) $\lambda_2 = 100$ %	Pedestrians 1 ($1/\lambda_1 = 7.72$) $\lambda_1 = 120$ % Pedestrians 2 ($1/\lambda_2 = 42.58$) $\lambda_2 = 100$ %	Pedestrians 1 ($1/\lambda_1 = 5.79$) $\lambda_1 = 140$ % Pedestrians 2 ($1/\lambda_2 = 42.58$) $\lambda_2 = 100$ %	Pedestrians 1 ($1/\lambda_1 = 3.86$) $\lambda_1 = 160$ % Pedestrians 2 ($1/\lambda_2 = 42.58$) $\lambda_2 = 100$ %	Pedestrians 1 ($1/\lambda_1 = 2.895$) $\lambda_1 = 170$ % Pedestrians 2 ($1/\lambda_2 = 42.58$) $\lambda_2 = 100$ %
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 Interval (95 %)	(3.58 to 3.67)	(4.27 to 4.56)	(6.67 to 6.96)	(17.97 to 19.18)	(243.27 to 290.06)
Mean capacity for the time interval of 3^h Q_4 (PCU's$_4$)	**2048**	**2048**	**2048**	**2046**	**1956**
SD	48	48	48	47	35
Confidence Interval 95 %	(2039 to 2058)	(2039 to 2058)	(2039 to 2058)	(2037 to 2056)	(1949 to 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$_4$*

PCUs arrivals ($1/\lambda_3$ = 10.06) ($1/\lambda_4$ = 5.26) ($1/\lambda_5$ = 6.36)	Arrivals of pedestrians 2 (sec./pedestrian)				
	Pedestrians 2 ($1/\lambda_2$ = 42.58) λ_2 = 100 % Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 %	Pedestrians 2 ($1/\lambda_2$ = 34.064) λ_2 = 120 % Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 %	Pedestrians 2 ($1/\lambda_2$ = 25.548) λ_2 = 140 % Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 %	Pedestrians 2 ($1/\lambda_2$ = 17.032) λ_2 = 160 % Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 %	Pedestrians 2 ($1/\lambda_2$ = 12.774) λ_2 = 170 % Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 %
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 Interval (95 %)	(3.58 to 3.67)	(3.75 to 3.86)	(4.09 to 4.21)	(4.85 to 5.03)	(5.76 to 5.99)
Mean capacity for the time interval of 3^h Q_4 (PCU's$_4$)	**2048**	**2048**	**2048**	**2048**	**2048**
SD	48	48	48	48	48
Confidence Interval (95 %)	(2039 to 2058)	(2039 to 2058)	(2039 to 2058)	(2039 to 2058)	(2039 to 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$_4$*

PCUs arrivals ($1/\lambda_3$ = 10.06) ($1/\lambda_4$ = 5.26) ($1/\lambda_5$ = 6.36)	Arrivals of pedestrians 1 and pedestrians 2 (sec./pedestrian)				
	Pedestrians 1 ($1/\lambda_1$ = 9.65) λ_1 = 100 % Pedestrians 2 ($1/\lambda_2$ = 42.58) λ_2 = 100 %	Pedestrians 1 ($1/\lambda_1$ = 7.72) λ_1 = 120 % Pedestrians 2 ($1/\lambda_2$ = 34.064) λ_2 = 120 %	Pedestrians 1 ($1/\lambda_1$ = 5.79) λ_1 = 140 % Pedestrians 2 ($1/\lambda_2$ = 25.548) λ_2 = 140 %	Pedestrians 1 ($1/\lambda_1$ = 3.86) λ_1 = 160 % Pedestrians 2 ($1/\lambda_2$ = 17.032) λ_2 = 160 %	Pedestrians 1 ($1/\lambda_1$ = 2.895) λ_1 = 170 % Pedestrians 2 ($1/\lambda_2$ = 12.774) λ_2 = 170 %
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 Interval (95 %)	(3.58 to 3.67)	(4.68 to 4.83)	(7.63 to 8.03)	(34.91 to 38.94)	(896.77 to 962.27)
Mean capacity for the time interval of 3^h Q_4 (PCU's$_4$)	**2048**	**2048**	**2048**	**2043**	**1694**
SD	48	48	48	47	37
Confidence Interval (95 %)	(2039 to 2058)	(2039 to 2058)	(2038 to 2057)	(2033 to 2052)	(1687 to 1701)

and capacity of the main traffic flow of PCU$_4$ are still admissible (Table 3);

b) beside the fixed variables (λ_3, λ_4, λ_5) the frequency of pedestrians 1 (λ_1) has been fixed. In the analysis, values λ_2 have been changed or increased to the same level as the frequency of pedestrians 1 (Table 4);

c) the variables (λ_3, λ_4, λ_5) have been fixed. In the analysis, values of frequency λ_1 and λ_2 have been changed or increased to the level that the mean waiting time and capacity of the main traffic flow of PCU$_4$ are still admissible (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 [13]. 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.

2.4 Discussion – Interpretation of the Simulation Results

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 "Old bridge" towards "Main square" 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 (λ_2 = 0.02352 ped/sec) is relatively small considering the pedestrian frequency (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.

The actual roundabout capacity is definitely dependent on the simultaneous consideration of pedestrian frequencies λ_1 and λ_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.

3 CONCLUSION

In this paper the influence of the strong pedestrian traffic flow on the capacity of the one-lane three-armed roundabout using the discreet numeric simulations modelling is presented. The analysis presented in this paper provides a new complex confirmation of the traffic flow (the simultaneous use of the main and the circulating flow) and the influence of the strong pedestrian flow (the use of multi-channel system) on the capacity of the roundabout.

First, the main theoretical background for the analysis of the traffic flow of motorised vehicles – personal car units (PCU) and pedestrians in the roundabout is presented. Since in roundabouts the pedestrian traffic flow is given priority, the vehicles on entries/exits have to give way to pedestrians. Consequently, disturbances at entering/exiting of motorised vehicles occur and the motorised vehicle flow is disrupted. The more disrupted the motorized vehicle flow is, the lower the capacity of the roundabout. In case the flows towards the entry of the roundabout are disturbed, the minimum capacity is not reached. In case the flows towards the exit of the roundabout are disturbed, the maximum capacity can get exceeded. Under real conditions, the entering and exiting of the motorised traffic flow are simultaneously disturbed and congestions are transferred from arm to arm, in clock-wise direction. For this purpose, the mathematical modelling of traffic flows with the use of discreet simulations has been used for the analysis of the influence of the pedestrian flow on the capacity of the roundabout, considering the statistically evaluated input data of the PCU and pedestrian traffic flows.

The main part of this paper consists of the discreet numeric simulation of the roundabout. The simulation model of the roundabout is general, i.e. 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 on Koroška Street in Maribor have been used. The results (the capacity of motorised vehicles Q_4) acquired with measurements of the traffic flow and simulation analyses match well (Tables 4, 5 and 6), which means that simulation analysis results give a good prediction for the evaluation of the waiting period and waiting queues of motorized vehicles in an individual 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 great reserve available in relation to the capacity of pedestrians 1 and 2 (up till 60 % of current frequencies λ_1 in λ_2). Since the traffic flow of PCU is going to increase in the future, we assume that the capacity reserve will get lower, but it will still be great enough to allow an undisturbed traffic flow of PCU. It should be mentioned that the analysis results refer to the counting of traffic flow carried out in the morning peak hour, only on the treated part of the roundabout. In the continuation of this research it would be reasonable to analyse the influence of the mean waiting time and PCU capacity on the whole roundabout and in the afternoon peak hour, considering a different pedestrian speed. Different types of motorised vehicles and pedestrians (dimensions, reaction times, velocities, accelerations, etc.) should be taken into account.

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