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Analiza vpliva prometnega toka pešcev na prepustno zmožnost krožišča z uporabo diskretnih simulacij

An Analysis of the Influence of Pedestrians' Traffic Flow on the Capacity of a Roundabout Using the Discrete Simulation Method

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Podobno kakor v običajnih nesemaforiziranih križiščih lahko tudi pri krožiščih, v posebnih prometnih razmerah, prihaja do bistvenega zmanjšanja prepustnosti. V takih primerih je značilno, da je prometni tok pešcev in/ali kolesarjev pri prečkanju enega ali več krakov krožišča tako močan, da vpliva na polnjenje ali na praznjenje krožišča. Namen prispevka je ponazoriti, kako lahko uporaba diskretnih simulacij prispeva k odločitvi o izvedbi krožišča, oziroma ali bo krožišče primerno izpolnjevalo pogoj zmogljivosti ob pričakovanem prometnem toku pešcev in/ali kolesarjev. Predlagan je nov način obravnave problematike dimenzioniranja krožišč z vidika matematičnega modeliranja prometnih tokov z uporabo metode diskretnih simulacij, z upoštevanimi statistično ovrednotenimi vhodnimi podatki za prometni tok vozil in pešcev. Rezultati simulacij so uporabni pri določanju prepustnosti načrtovanih krožišč, ki bodo delovali v različnih prometnih okoliščinah. Predstavljen model izhaja iz sprejemljive časovne praznine v prometnem toku pešcev, ki jo uporabljajo motorna vozila za uvažanje in izvažanje iz krožišča, če upoštevamo, da imajo pešci prednost. Simulacijska analiza je preverjena na dejanskem primeru montažnega krožišča v Mariboru, na Koroški ulici, kjer so bile izvedene tudi potrebne meritve prometnega toka motornih vozil ter pešcev in kolesarjev. Postopek, prikazan v prispevku, predstavlja poleg znanstvenega postopka matematičnega modeliranja tudi praktično metodo za pomoč pri odločanju o smiselnosti izvedbe krožišča v primeru močnega toka pešcev in/ali kolesarjev.

(Ključne besede: krožišča, tokovi prometni, analize vplivov, modeli simulacijski)

Like with other non-traffic-lighted intersections, the capacity of roundabouts can be reduced by special traffic conditions. In such cases the pedestrian's and/or cyclist's traffic flow, crossing one or more roundabout arms, is the size that influences the roundabout filling or emptying. The purpose of this paper is to show how the use of discrete simulation methods contributes to the decision on implementing a roundabout, or to help decide if the roundabout is going to fulfil appropriately the condition of the expected flow of pedestrians and/or cyclists. A new approach is suggested for dimensioning roundabouts, with mathematical modelling of the traffic flows using the discrete simulation method, and considering the statistically evaluated entry data for vehicles' and pedestrians' traffic flows. The simulation results are useful when determining the capacity of foreseen and suggested roundabouts, which will function in different circumstances. The presented model derives from the expected time void in the vehicles' traffic flow, used by the pedestrians, assuming their right of way when joining the traffic. The simulation analysis was verified on a real example of a montage roundabout in Koroška Street in Maribor, where measurements of the motorised vehicles' traffic flow, and pedestrians' and cyclists' traffic flow were made. The procedure, shown in the paper, along with the scientific approach to mathematical modelling, presents a practical method, helpful when deciding whether to implement a roundabout in the case of heavy pedestrians' and/or cyclists' traffic flows.

(Keywords: roundabouts, traffic flow, influence analysis, simulation models)

0 UVOD

V krožiščih z enim voznim pasom v krožnem vozišču se lahko, zaradi močnega toka pešcev in/ali kolesarjev, pojavijo problemi s polnjenjem in praznjenjem krožišča. Vozila na uvozih in izvozih iz krožišča morajo pešcem in kolesarjem praviloma odstopiti prednost. Zaradi tega prihaja do motenj v prometnem toku motornih vozil, ki je prednostnem v smislu dimenzioniranja krožišča in njegove zmogljivosti in zaradi tega povzročenimi zastoji [1]. V primeru, da je tok motornih vozil, ki ga prečka tok pešcev in/ali kolesarjev, usmerjen proti uvozu, postane vprašljivo doseganje najmanjše zmogljivosti krožišča. V primeru, da je tok motornih vozil, ki ga prečka tok pešcev in/ali kolesarjev, usmerjen proti izvozu, prihaja do prekoračitve največje zmogljivosti krožišča [2]. Možnost nastanka blokade krožišča se lahko ugotavlja na več načinov. V preteklosti so različni avtorji ([4] in [5]) uporabljali različne načine izračuna zmogljivosti krožišč in različne načine določanja vpliva toka nemotoriziranih udeležencev na zmogljivost krožišča. Skupna lastnost vseh teh postopkov je obilica matematičnih izračunov [6] in poenostavitev, da bi izračun sploh bil mogoč. Zaradi tega so se takšni izračuni uporabljali le v izjemnih primerih. Med preprostejše metode, pri katerih se uporablja samo diagram ali ena enačba, sodijo nemška metoda za določanje vpliva pešcev [7] in nizozemska metoda za določanje vpliva kolesarjev [8] na prepustnost enopasovnega krožišča. Dandanes po svetu prevladujeta dve skupini metod za določanje zmogljivosti krožišč, s tem pa tudi vpliva toka pešcev in kolesarjev na zmanjšanje njihove zmogljivosti. V prvo skupino sodijo deterministične, v drugo skupino pa naključnostne metode.

V zadnjem času se vse bolj povečuje tudi pomen simulacijskih metod, za kar so zaslužni predvsem vedno bolj zmogljivi računalniki in velike možnosti ustvarjanja zapletenih matematičnih modelov, ki omogočajo dobro primerljivost rezultatov z dejanskimi razmerami. V prispevku predstavljen model izhaja iz sprejemljive časovne praznine v prometnem toku pešcev oziroma kolesarjev, ki jo uporabljajo motorna vozila za uvažanje in izvažanje iz krožišča, če upoštevamo, da imajo pešci oziroma kolesarji prednost. V predstavljenem modelu je obravnavan osamljen krak krožišča oziroma uvoza v krožišče brez vpliva krožečega toka v vozišču. Predpostavljena je enaka hitrost posameznih

0 INTRODUCTION

With one-lane roundabouts, problems with entering and exiting the roundabout can occur due to large traffic flows of pedestrians and/or cyclists. Vehicles on entries and exits should, as a rule, give priority to pedestrians and cyclists. For this reason, disturbances occur in the main vehicle flow, considered as a priority when dimensioning a roundabout intersection and its capacity for the resulting congestions [1]. When a flow of vehicles, traversed by pedestrians and/or cyclists, is oriented towards an entry, achieving the minimum capacity of the roundabout becomes questionable. When a flow of vehicles, traversed by pedestrians and/or cyclists, is oriented towards an exit, the maximum capacity gets exceeded [2]. The possibility of a roundabout blockage can occur in more ways. In the past, many authors ([4] and [5]) used different ways of calculating the capacity of roundabouts and different approaches for determining the influence of the flow of non-motorised traffic participants on the capacity of a roundabout. The common feature of all the approaches is an abundance of mathematical calculations [6] and simplifications to make the calculation possible in the first place. This is why this kind of calculation has been used in exceptional cases only. Among the simpler methods, where only a diagram or one equation are used, are the German method for determining the influence of pedestrians [7] and the Dutch method for determining the influence of cyclists [8] on the capacity of a one-lane roundabout. Nowadays, two groups of methods for determining the capacity of a roundabout, and the resulting influence of pedestrians' and cyclists' flow on the reduction of its capacity are dominant in the world. In the first group there are the deterministic methods, and in the second group are the stochastic methods.

Lately, the significance of simulation methods is also increasing, with the most credit going to increasingly capable computers and the numerous possibilities for creating complex mathematical models that enable good comparability of the results with the actual circumstances. The presented model derives from the expected time void in the pedestrians' traffic flow, used by the vehicles for entering and exiting the roundabout, assuming their right of way when joining the traffic. In the proposed model only a separate arm of the roundabout is considered, without the influence of a circular flow of motorised vehicles on the circulatory roadway. The equal velocity of the motorised vehicles, as well as for pedestrians is considered. The arrivals of motornih vozil kakor tudi enaka hitrost posameznih pešcev. Prihodi pešcev so obravnavani posamezno pešec za pešcem, v eni vrsti. Simulacijska analiza je uporabljena na dejanskem primeru montažnega krožišča v Mariboru, na Koroški ulici, kjer so bile izvedene tudi vse potrebne meritve. Postopek, prikazan v prispevku, je poleg znanstvenega načina matematičnega modeliranja tudi pripomoček za pomoč pri odločanju o primernosti izvedbe krožišča v primeru močnega toka pešcev in/ali kolesarjev.

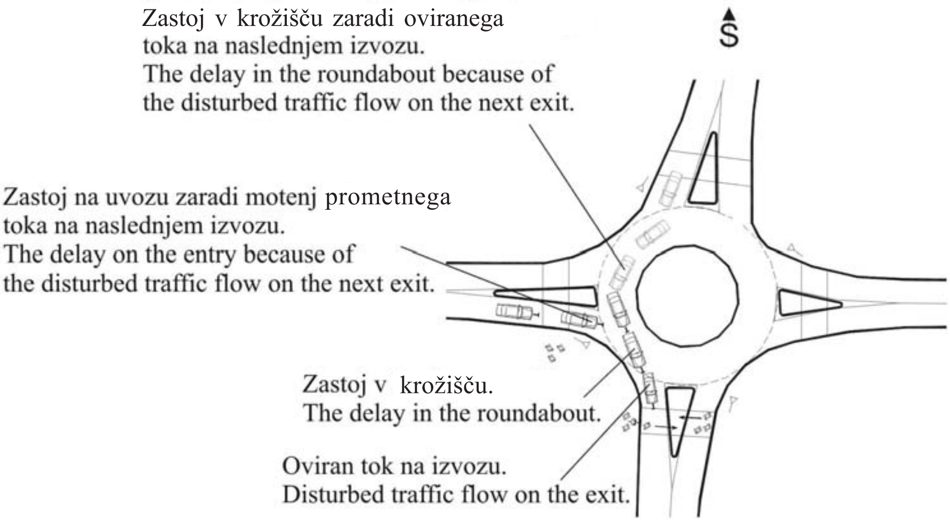
1 OPIS PROBLEMATIKE

V osnovi moramo, pri določanju zmanjšanja zmogljivosti krožišča zaradi močnega toka pešcev in/ali kolesarjev, ločiti dva primera. V prvem primeru prečni prometni tok pešcev sicer vpliva na prepustno zmožnost krožišča, toda krožišče deluje. V drugem primeru pa je vpliv pešcev in/ali kolesarjev tolikšen, da obstaja možnost, da nastajajo daljši zastoji pri uvozu in izvozu iz krožišča, ki pa se potem prenašajo na sosednje krake krožišča. Če je dolžina vozil v vrsti pri izvozu iz krožišča tako dolga, da doseže predhodni uvoz, prihaja do problemov zasedenosti krožišča in lahko pride do zastoja v celotnem krožišču. Navedena problema polnjenja in praznjenja krožišča v dejanskih razmerah se največkrat pojavita hkrati. V dejanskih razmerah je prav tako običajno, da močan tok pešcev prečka le enega od krakov krožišča, čeprav obstajajo tudi primeri, ko tok pešcev »seka« vse krake hkrati. V takšnih primerih pride do zastoja v krožišču prej. V nadaljevanju je, zaradi preprostejše razlage, obravnavan primer, ko močen tok pešcev prečka le en krak krožišča. Prednostni tok pešcev prečka (južni) krak krožišča (sl. 1). Časovni presledki med dvema zaporednima pešcema so zadostni, zato jih vozila na izvozu iz krožišča uporabljajo in nemoteno zapuščajo krožišče. Tok vozil pri izvozu iz krožišča je stabilen. S povečanjem jakosti toka pešcev prihaja do zmanjšanja časovnih presledkov med enotami tega prometnega toka. Občasno se pojavljajo tudi primeri, ko so posamezni časovni presledki med enotami toka pešcev krajši od sprejemljivih. V takšnih primerih vozilo čaka v niši med zunanjim robom krožišča in robom prehoda za pešce/kolesarje. Tok je še vedno stabilen, vendar občasno moten (oviran).

the pedestrians are supposed to be separate, one by one, in single file. The simulation analysis was verified on a real example of a montage roundabout in Koroška Street in Maribor, where all the necessary traffic-flow measurements were made. The procedure, shown in the paper, along with the scientific approach to mathematical modelling, presents an instrument that is helpful when deciding how reasonable it is to implement a roundabout in the case of strong traffic flows of pedestrians and/or cyclists.

1 DESCRIPTION OF THE PROBLEM

When defining the capacity reduction of roundabouts, two different samples can be distinguished because of large traffic flows of pedestrians and/or cyclists. In the first case, the traversed pedestrian’s and/or cyclist’s flow influenced the permeable capacity of the roundabout, but it still works. In second case, the influence of the pedestrian’s and/or cyclist’s traffic flow was of such size that bottlenecks on roundabout entry and exit are possible, which could also be extended to the adjacent roundabout arms. If the length of the vehicles in the queue is so long that it stretches back to the previous entry point, problems with occupation of the roundabout arise and a blockage of the entire roundabout can occur. The mentioned problems of entering and exiting a roundabout in real conditions usually happen simultaneously. In real circumstances it is also usual that those intensive pedestrian flows traverse only one arm of the roundabout, although in some cases the pedestrians’ flow “cuts” all the arms at once. In these cases the blockage of the roundabout occurs earlier. In the following is an example of when a strong pedestrian flow traverses only one arm, because of the easier explanation. The right-of-way pedestrian flow traverses the south arm of the roundabout (Figure 1). The time interspaces between two consecutive pedestrians are long enough; therefore, the vehicles exiting the roundabout use them and exit the roundabout undisturbed. The vehicle flow on the exit is stable in this case. With an increasing strength of pedestrian flow the time interspaces between the traffic-flow units are reduced. Situations occasionally occur when the individual time interspaces between the pedestrian flow units are shorter than 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 it is disturbed.



Sl. 1. *Nastanek zastoja v krožišču [3]*
Fig. 1. *Queue formation on a roundabout [3]*

Z nadaljnjim povečevanjem toka pešcev se razmere vedno bolj slabšajo, oziroma niša za čakanje pri izvozu iz krožišča postaja ves čas zasedena. Zaradi tega se vozila kopičijo na krožišču do predhodnega uvoza in onemogočajo uvoz vozil v krožišče. Prometni tok med južnim in zahodnim krakom krožišča je moten (sl. 1). V tem primeru je mogoče odvijanje prometnega toka le še na preostalih delih krožišča. V primeru, da je katero od vozil na preostalih treh uvozih usmerjeno proti zastojnemu izvozu, prihaja do zapolnitve še enega krožnega odseka (med zahodnim in severnim krakom – slika 1), kar povzroči zastoj tudi zahodnega kraka krožišča. Zastoj se prenaša od izvoza iz krožišča do prejšnjega (gledano v nasprotni smeri vožnje v krožišču) uvoza v krožišče in od tu zopet naprej na prejšnji izvoz. Celoten postopek se lahko ponavlja v nasprotni smeri vožnje do popolnega zastoja krožišča. V enopasovnem krožišču s prostorom za čakanje enega vozila v niši med prehodom za pešce in zunanjim robom krožišča se torej lahko v splošnem pojavijo trije primeri, in sicer:

- časovni presledki med posameznimi enotami prečnega toka pešcev so zadostni za prehod vozil, zato ni čakajočih vozil v niši;
- časovni presledki med posameznimi enotami prečnega toka pešcev so še vedno zadostni za prehod vozil, čeprav prihaja do čakanja vozil v niši;

With an additional increase in the pedestrian flow the conditions get worse and the waiting place on the exit of the roundabout becomes occupied all the time. For this reason the vehicles are congested on the circulatory roadway towards the preceding entry, thus preventing entry to the roundabout. The traffic flow between the south and the west arms is disturbed. In this case traffic flow is possible only on other parts of the circulatory roadway. In the case that one of the vehicles on the other three entries is directed towards the blocked exit, another circular segment gets filled (between the west and the north arms – Figure 1), which causes the blockage of the west arm of the roundabout. The blockage is transferred from an exit towards the preceding (opposite to the driving direction) entry to the roundabout and from here towards the preceding exit. The entire procedure can repeat itself in the direction opposite to the driving until the roundabout is completely blocked. In a one-lane roundabout with a waiting space for one vehicle in the waiting place between the pedestrian crossing and the outside edge of the circulatory roadway the following three situations can generally occur:

- time interspaces between the individual units of transverse pedestrian flow are sufficient for vehicle flow, and so there are no waiting vehicles in the waiting place;
- time interspaces between the individual units of transverse pedestrian flow are still sufficient for vehicle flow, although vehicles do wait in the waiting place;

- časovni presledki med posameznimi enotami prečnega toka pešcev so premajhni, niša je ves čas zasedena in vsako naslednje vozilo čaka na krožišču.

Kolikokrat se lahko pojavijo opisani primeri, kakšni so pogoji za nastanek opisanih primerov, kateri pogoji morajo biti izpolnjeni za nastanek zastoja enega kraka krožišča in pri kolikšni prometni obremenitvi pešcev ali motornega prometa se motnja iz enega kraka krožišča lahko prenese na sosednji krak, so vprašanja, katerih odgovori določajo vpliv toka pešcev na prepustno zmožnost, tj. zmogljivost enopasovnega krožišča. Očitno je, da tako zapletenih vplivov in medsebojnih delovanj različnih spremenljivk ni mogoče reševati brez uporabe ustreznih matematičnih modelov oziroma diskretnih simulacij prometnega toka motornih vozil, pešcev in/ali kolesarjev. V nadaljevanju so podana osnovna teoretična izhodišča za matematično analizo prometnega toka v obravnavanem krožišču.

2 TEORETIČNA IZHODIŠČA PRI ANALIZIRANJU PROMETNEGA TOKA V KROŽIŠČU

Pri načrtovanju krožišča nas v največji meri zanima njegova zmogljivost v odvisnosti od prometnega toka (*i*) motornih vozil ter (*ii*) pešcev in kolesarjev. Temeljno pravilo pri vsakem krožišču (izjema so semaforizirana krožišča) je, da imajo pešci in kolesarji prednost pred motornimi vozili. Pri določitvi zmogljivosti krožišča izhajamo iz skupne frekvence prometnega toka motornih vozil ter pešcev in kolesarjev, ki se križajo na posameznem kraku krožišča. Celotno zmogljivost (motornih vozil ter pešcev in kolesarjev) posameznega kraka krožišča lahko izrazimo z naslednjo poenostavljeno odvisnostjo, pri čemer je:

μ_1 – največja zmogljivost prometnega toka motornih vozil v izbrani časovni enoti,

μ_2 – največja zmogljivost prometnega toka pešcev in kolesarjev v izbrani časovni enoti,

λ_1 – dejanska zmogljivost prometnega toka motornih vozil z upoštevanjem pešcev in kolesarjev v izbrani časovni enoti,

λ_2 – dejanska zmogljivost prometnega toka pešcev in kolesarjev v izbrani časovni enoti.

- Izkoristek ρ_1 posameznega kraka krožišča za motorna vozila je enak naslednji odvisnosti:

- time interspaces between the individual units of transverse 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 creation of these situations, what conditions have to be fulfilled for a blockage of one arm of the roundabout 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 a one-lane roundabout. It is obvious that such complex influences and mutual actions of different variables cannot be solved without appropriate mathematical models or discrete simulations of the motorised and non-motorised traffic flows. In the following, the basic theoretical backgrounds for the mathematical analysis of a traffic flow in a given roundabout are presented.

2 THEORETICAL BACKGROUNDS FOR ANALYSING THE TRAFFIC FLOW IN A ROUNDABOUT

When planning a roundabout, its capacity in relation to the traffic flow (i) of motorised vehicles and (ii) pedestrians and cyclists are the main interest. The general rule in every roundabout (roundabouts with traffic lights are an exception) is that pedestrians and cyclists have priority with regard to the motorised vehicles. When determining the capacity of a roundabout, the combined frequency of the traffic flow of vehicles, pedestrians and cyclists, crossing each other on an individual arm of a roundabout are derived. The total capacity (motorised vehicles, pedestrians and cyclists) in an individual arm of a roundabout can be presented with the following simplified relation dependence:

μ_1 – maximum capacity of a traffic flow of motorised vehicles in a given time period,

μ_2 – maximum capacity of a traffic flow of pedestrians and cyclists in a given time period,

λ_1 – actual capacity of a traffic flow of motorised vehicles, considering pedestrians and cyclists in a given time period,

λ_2 – actual capacity of a traffic flow of pedestrians and cyclists in a given time period.

- The utilisation rate ρ_1 of an individual arm of a roundabout for motorised vehicles is given by the following relation:

$$\rho_1 = \frac{\lambda_1}{\mu_1} \le 1 \quad (1).$$

- Izkoristek ρ_2 posameznega kraka krožišča za pešce in kolesarje je enak naslednji odvisnosti:

- The utilisation rate ρ_2 of an individual roundabouts' arm for pedestrians and cyclists is given by the following relation:

$$\rho_2 = \frac{\lambda_2}{\mu_2} = 1 \quad \text{kjer je/where} \quad \lambda_2 = \mu_2 \quad (2).$$

S poenostavljeno odvisnostjo (2) smo pokazali, da je dejanska zmogljivost pešcev in kolesarjev, zaradi pogoja prednosti le-teh pred motornimi vozili, zmeraj enaka največji zmogljivosti. Drugačno odvisnost prikazuje izraz za zmogljivost motornih vozil (1), ki je močno odvisna od prometnega toka pešcev in kolesarjev. Pri analizi krožišča oziroma posameznih krakov krožišča želimo ugotoviti, pri katerem prometnem toku pešcev in kolesarjev je prepustnost motornih vozil še smotrna, da ne prihaja do prevelikih čakalnih dob (časov) in čakalnih vrst motornih vozil.

Prihode motornih vozil ter pešcev in kolesarjev v posamezne krake krožišča lahko obravnavamo kot sistem čakalne vrste z enim strežnim mestom [12]. Pri določitvi ustreznega sistema čakalne vrste izhajamo iz pogoja, da so prihodi motornih vozil porazdeljeni po Poissonovi statistični porazdelitvi. Prav tako upoštevamo, da je čas med dvema zaporednima prihodoma pešcev in kolesarjev podan po Poissonovi statistični porazdelitvi. Zaradi zveze med Poissonovo in eksponentno statistično porazdelitvijo je treba določiti naslednjo povezavo. Če je število prihodov motornih vozil ali pešcev in kolesarjev v določenem časovnem koraku t podano po Poissonovi porazdelitvi s povprečno stopnjo prihodov na časovno enoto enako λ in s srednjo vrednostjo $\lambda \cdot \tau$, potem so časi med prihodoma dveh zaporednih vozil ali pešcev in kolesarjev podani po *eksponentni* porazdelitvi s srednjo vrednostjo $1/\lambda$ [13].

M – se navezuje na Poissonovo porazdelitev števila prihodov motornih vozil pešcev in kolesarjev na časovno enoto,

D – navezuje se na stalno oz. deterministično porazdelitev časa, ki je potreben za vožnjo motornih vozil prek prehoda za pešce ter prehoda pešcev in kolesarjev na drugo stran vozišča,

1 – v sistemu je samo eno strežno mesto, ki se navezuje na prehod za pešce,

∞ – prihod v sistem je določen z neskončnim tokom motornih vozil ter pešcev in kolesarjev,

The simplified relation (2) presents the actual capacity of pedestrians and cyclists (due to the priority with regard to the motorised vehicles) that are always the same as the maximum capacity. A different relation is presented by the expression for the capacity of motorised vehicles (1), which strongly depends on the traffic flow of pedestrians and cyclists. When analysing a roundabout or individual arms of it, one has to establish at what traffic flow of pedestrians and cyclists the capacity of motorised vehicles is still reasonable, so that too long waiting periods and waiting lines of motorised vehicles do not occur.

The arrivals of motorised vehicles, pedestrians and cyclists into the individual arms of a roundabout can be treated as a system of a waiting line with one serving place [12]. When determining the appropriate system of the waiting line the basic condition, that the arrivals of motorised vehicles are distributed according to Poisson's statistical distribution, is taken into account. The condition that the time between two consecutive arrivals of pedestrians or cyclists is distributed according to Poisson's statistical distribution is also considered. Due to the connection between Poisson's and the exponent statistical distribution, the following relation has to be defined. If the number of arrivals of motorised vehicles, pedestrians or cyclists in a given time interval t is distributed according to Poisson's distribution with an average degree of arrivals in a time unit λ and a medium value $\lambda \cdot \tau$, then the times between the arrivals of two consecutive vehicles, pedestrians or cyclists, are distributed according to the exponent distribution with a medium value of $1/\lambda$ [13].

M – according to the Poisson's distribution of the number of arrivals of motorised vehicles, pedestrians and cyclists in a given time unit,

D – according to the constant or deterministic distribution of time, required for the driving of motorised vehicles by the pedestrian crossing and the crossing of pedestrians and cyclists to the other side of the roadway,

1 – only one serving station exists in the system, which is in connection to the pedestrian crossing,

∞ – arrival to the system is determined by an infinite flow of motorised vehicles, pedestrians and cyclists,

∞ – sistem omogoča neskončno mnogo voženj motornih vozil prek prehoda za pešce ter prehodov pešcev in kolesarjev na drugo stran vozišča,

FIFO – enota (motorno vozilo, pešec ali kolesar), ki pride v sistem prva, je tudi prva postrežena.

Sistem *M*/*D*/1/∞/∞/*FIFO* za prometni tok motornih vozil ter prometni tok pešcev in kolesarjev je za primer obravnavanega kraka krožišča prikazan na sliki 2.

Zaradi dveh neodvisnih prometnih tokov (motornih vozil ter pešcev in kolesarjev) pomeni posamezen krak krožišča skupek dveh neodvisnih sistemov čakalnih vrst, in sicer:

- *M*/*D*/1/∞/∞/*FIFO* za prometni tok motornih vozil in

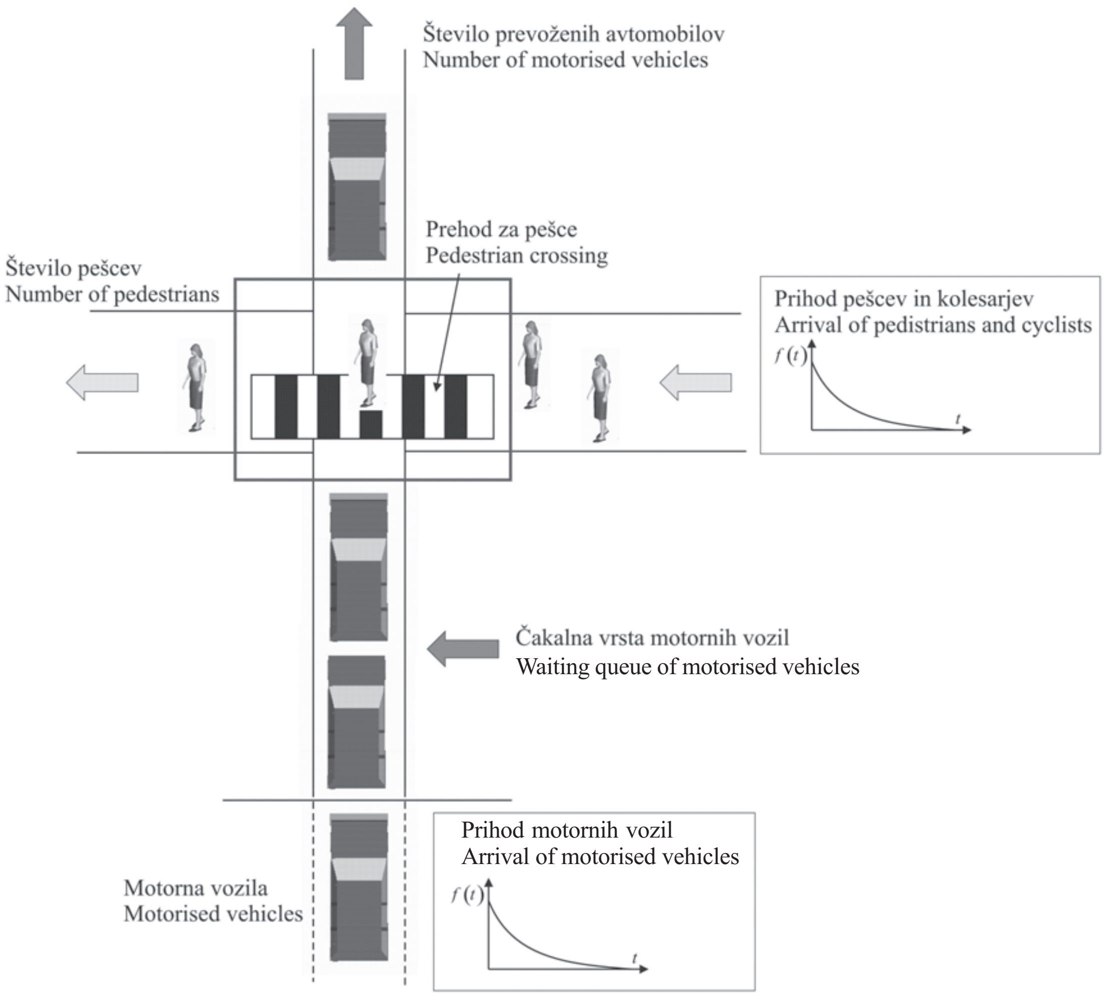
∞ – system enables infinite driving of motorised vehicles over the pedestrian crossing and the crossing of pedestrians and cyclists to the other side of the carriageway,

FIFO – *Unit (motorised vehicle, pedestrian or cyclist),* which when coming into the system first is served first.

The *M*/*D*/1/∞/∞/*FIFO* system for a traffic flow of motorised vehicles and the pedestrians' and cyclists' traffic flows is schematically shown in Figure 2 for the example of the roundabout arm in question.

Because of the two independent traffic flows (motorised vehicles, and pedestrians and cyclists), an individual arm in a roundabout presents a combination of two independent waiting-line systems:

- M/D/1/∞/∞/FIFO for the motorised vehicles' traffic flow,



Sl. 2. *Prikaz enega kraka krožišča v obliki sistema M/D/1/∞/∞/FIFO*
Fig. 2. *An individual roundabouts' arm in the form of the M/D/1/∞/∞/FIFO system*

- *M*/*D*/1/∞/∞/*FIFO* za prometni tok pešcev in kolesarjev.

Medtem ko je prometni tok motornih vozil tipični sistem *M*/*D*/1/∞/∞/*FIFO*, je prometni tok pešcev in kolesarjev prilagojen sistem *M*/*D*/1/∞/∞/*FIFO*, saj v omenjenem sistemu nikoli ne pride do čakalnih dob in čakalne vrste. Omenjeno trditev lahko pojasnimo z dejstvom, da imajo v krožišču pešci in kolesarji v vsakem primeru prednost pred motornimi vozili. Zaradi zapletenosti in nedoločenosti sistema, bi sistem čakalnih vrst posameznega kraka krožišča in sistema čakalne vrste celotnega krožišča težko obravnavali analitično. Tako je mogoča rešitev problema uporaba metode diskretnih numeričnih simulacij, ki je predstavljena v nadaljevanju.

3 SIMULACIJA PROMETNEGA TOKA V DEJANSKEM KROŽIŠČU

Analiza prometnih tokov z uporabo diskretnih numeričnih simulacij pomeni uspešen način analize zahtevnejših nivojskih in večnivojskih križišč z vidika zmogljivosti ([9] do [11]). Glede na diskretne modele in način prometnega dogajanja lahko, v splošnem, simulacijske metode razdelimo v dve osnovni skupini, in sicer na (*i*) makroskopske in (*ii*) mikroskopske modele. Makroskopski modeli združujejo vozila in sama potovanja po skupinah, pri čemer se prometni tok kaže kot statistični model, medtem ko rezultat predstavlja povprečje v določenem času. Pri makroskopskih modelih je poudarek na samih povezavah, križišča so v modelu poenostavljena. Makroskopski modeli so, nasprotno od mikroskopskih modelov, osredotočeni na dolgo dobo načrtovanja. Z mikroskopskimi modeli »opisujemo« vsako posamezno vozilo, pešca, kolesarja itn. s stvarnimi lastnostmi (izmere, hitrosti, pospeški itn.). Mikroskopski modeli se uporabljajo za analize prometnih tokov v kratki načrtovalni dobi.

Glede na zapletenost analitičnega modela krožišča in uporabnosti diskretne simulacijske tehnike, smo za analizo zmogljivosti krožišča uporabili diskretne numerične simulacije. V tem prispevku smo za analizo krožišča uporabili programsko orodje AutoMod [14], ki se uporablja predvsem za izvajanje diskretnih numeričnih simulacij sistemov notranje logistike [15] ter vseh drugih logističnih diskretnih sistemov. Le-ta omogoča uporabniku zanesljivo orodje pri načrtovanju ali

- M/D/1/∞/∞/FIFO for the pedestrians’ and cyclists’ traffic flow.

While the motorised vehicles’ traffic flow represents a typical M/D/1/∞/∞/FIFO system, the pedestrians’ and cyclists’ traffic flow system M/D/1/∞/∞/FIFO is modified, since in the mentioned system the waiting periods and the waiting line never occur. This assertion can be explained by the fact that in a roundabout pedestrians and cyclists have priority over the motorised vehicles. Because of the complexity and non-determination of the system, the waiting line system of an individual arm of a roundabout and the waiting line system of the entire roundabout is problematic for an analytical treatment. Therefore, a possible solution to the problem is the use of the discrete numeric simulations method, which is presented in the following section.

3 SIMULATION OF THE TRAFFIC FLOW IN A REAL ROUNDABOUT

The analysis of traffic flows using discrete numeric simulations represents a successful way of analysing more complex crossroads and intersections from the point of capacity determination ([9] to [11]). According to discrete models and the way of action in traffic, simulation methods can be, generally, divided in two groups: (i) macroscopic and (ii) microscopic models. Macroscopic models combine vehicles and travelling among groups, and the traffic flow is represented by a statistical model; the result is presented as an average value after a certain time. With macroscopic models the emphasis is on the links themselves, the intersections are simplified in the model. Macroscopic models are, unlike microscopic models, focused on a long-term planning period. With a microscopic model every individual vehicle, pedestrian, cyclist, etc., can be described with real characteristics (dimensions, velocities, accelerations, etc.). Microscopic models are used for traffic-flow analyses in a short-term planning period.

Considering the complexity of the analytical model of a roundabout and the usage of a discrete simulation technique, discrete numeric simulations for the analysis of the capacity of a roundabout were used. In the proposed contribution the program code AutoMod [14] was used for the analysis of a roundabout. AutoMod [14] is used mostly for implementing discrete numeric simulations of internal logistic systems and all other logistic discrete systems. It offers the user a reliable tool for planning or reconstructing rekonstrukciji zapletenih in medsebojno odvisnih sistemov. Programsko orodje deluje v opravilnem sistemu Windows XP in je sestavljeno iz okolja, kjer modeliramo izbran sistem (predprocesor) in modul za izvedbo simulacije. Programsko orodje je sestavljeno iz posameznih programskih modulov, ki sestavljajo celoto programskega orodja AutoMod [14]. Pri modeliranju poljubnega sistema uporabljamo že vgrajene elemente (zvezni transporterji, avtomatizirana transportna vozila itn.), ki pomenijo določene sklope v izbranem postopku. Le-tem v vhodni datoteki (ang. *Source file*) z vpisom programske kode določimo lastnosti, ki ustrezajo dejanskemu stanju ter jih med seboj ustrezno povežemo. Z ukaznimi vrsticami določimo izvajanje simulacije ter analiziramo uspešnost in učinkovitost sistema.

V nadaljevanju so prikazani koraki simulacije in analize prometnega toka motornih vozil na montažnem trikrakem enopasovnem krožišču z močnim prometnim tokom pešcev in kolesarjev, na Koroški ulici v Mariboru (sl. 8). Izhajali smo iz dejanskih geometrijskih podatkov (sl. 9), kakor tudi vzorca prometnega toka pešcev in motornih vozil za vse krake križišča in prehode za pešce, ki smo ga izvedli s štetjem prometa in statistično ovrednotili dobljene podatke.

3.1 Vhodni podatki za izdelavo mikrosimulacijskega modela – analiza dejanskega stanja prometnih tokov, opravljena s štetjem prometa

Pri izdelavi simulacijskega modela za montažno trikrako enopasovno krožišče (sl. 3) smo upoštevali dejansko geometrijsko obliko krožišča (sl. 4) in hitrostne značilnice vozil in pešcev (pregl. 1).

Za potrebe analize je bilo opravljeno 15-urno štetje (6^{00} do 21^{00}), na vseh krakih križišča, ločeno za promet motornih vozil ter promet pešcev in kolesarjev (slika 4). V prispevku prikazujemo rezultate štetja motornega prometa (preglednica 2) in prometa pešcev ter kolesarjev (preglednica 2) na kraku A – smer "Stari most", na kraku B – smer Koroška c. vzhod (Kolosej) ter kraku C – smer Koroška c., ki so predmet obravnave pričujočega prispevka.

Na podlagi štetja prometnega toka motornih vozil ter pešcev in kolesarjev za vse cestne krake A, B in C montažnega krožišča na Koroški ulici v Mariboru smo dobljene podatke statistično

complex and inter-dependent systems [15]. The program code works in the Windows XP operating system and is constructed by the environment, where the chosen system is modelled (pre-processor) and a module for the starting of the simulation. The programming tool consists of individual programming modules that construct the programming tool AutoMod [14] as an integrity. When modelling a general system, already built-in elements (connection transporters, automates transport vehicles, etc.) that represent certain complexes in the chosen process, can be used. In the source file characteristics, which suit to the real situation and connect them appropriately, are determined. With the help of command lines the implementation of the simulation is determined and based on the acquired results of simulations the success and the efficiency of the system is analysed.

In the continuation steps of the simulation and the analysis of the motorised vehicles' traffic flow on a montage three-armed, one-lane roundabout with strong pedestrians' and cyclists' traffic flow on Koroška Street in Maribor (Figure 3) are shown. The actual geometrical data are derived from Figure 4 and from a sample of pedestrians' and motorised vehicles' flows for all the arms of the roundabout and pedestrian crossings, gathered by counting traffic and statistically evaluating the acquired data.

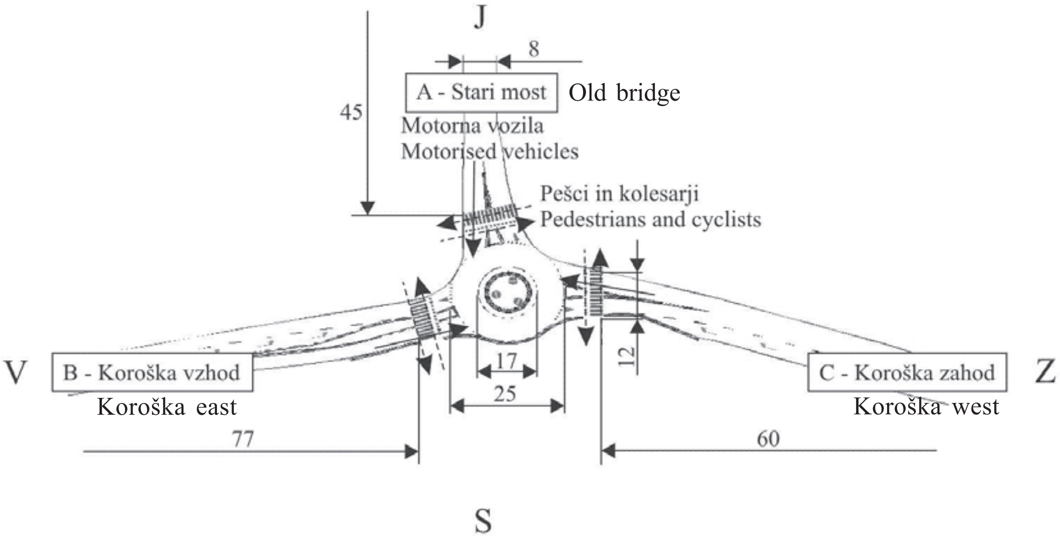
3.1 Input data for constructing a micro-simulation model – an analysis of the actual situation of traffic flows performed by counting traffic

When constructing a simulation model for a montage three-armed, one-lane roundabout (Figure 3) the actual geometry of the roundabout (Figure 4) and the velocity characteristics of vehicles and pedestrians (Table 1) were considered.

A 15-hour (6^{00} to 21^{00}) count was performed for the requirements of the analysis, on all the intersections' arms, separately for the motorised vehicle traffic and the pedestrian and cyclist traffic (Figure 4). The results of the motorised-vehicle traffic count (Table 2) and the pedestrian/cyclist traffic count (Table 2) on the Arm A – direction "old bridge", on the Arm B – direction Koroška Street east (Coloseum) and on the Arm C – direction Koroška Street, that are treated in this work were presented.

The acquired data was statistically evaluated, based on the traffic count of motorised vehicles and the pedestrians and cyclists for all the roads' arms A, B and C of the montage roundabout on the Koroška Street in

Sl. 3. *Montažno trikrako, enopasovno krožišče na Koroški ulici v Mariboru*
Fig. 3. *Montage three-armed, one-lane roundabout on Koroška Street in Maribor*



Sl. 4. *Geometrijska oblika obravnavanega krožišča (razdalje so v metrih)*
Fig. 4. *Geometry of the treated roundabout (distances are in meters)*

ovrednotili. V preglednici 2 so podrobneje prikazani podatki za posamezno konično uro, ki se navezujejo na prometni tok motornih vozil ter pešcev in kolesarjev na posameznih krakih krožišča A, B in C (slika 4). Izračunani so tudi povprečni časi med prihodoma dveh zaporednih vozil ($t = 1/\lambda$). Primer: število prihodov vozil v časovnem koraku 5 minut (300 s) je 43, porazdeljeno po Poissonovi statistični porazdelitvi, s povprečno stopnjo prihodov na časovno enoto λ = 43:300 in s srednjo vrednostjo $t{\cdot}\lambda$ = 43 MV; tako je povprečni čas med prihodoma dveh zaporednih vozil porazdeljen po eksponentni porazdelitvi s srednjo vrednostjo $1/\lambda$ = 6,98 sekund.

Maribor. In Table 2 the data for an individual rush-hour are presented, and they are connecting to the traffic flows of motorised vehicles, pedestrians and cyclists on the individual arms A, B and C of the roundabout (Figure 4). Additional, average times between two arrivals of successive motor vehicles are calculated ($t=1/\lambda$). Case: the number of motor-vehicle arrivals within a time interval of 5 minutes (300 s) is 43, distributed as a Poisson statistical distribution, with the average degree of arrivals per time unit λ=43:300 and with the medium value of $t{\cdot}\lambda$=43 MV; the average time between two arrivals of successive motor vehicles can be then determined using an exponential distribution with the medium value $1/\lambda$ = 6.98 seconds.

Preglednica 1. *Geometrijski in kinematični vhodni podatki*
Table 1. *Geometrical and kinematic input data*

Geometrijski vhodni podatki ***Geometrical input data***	
Zunanji premer krožišča Outside diameter of the roundabout	25 m
Notranji premer krožišča Inside diameter of the roundabout	17 m
Širina voznega pasu Width of the road	4 m
Širina prehoda za pešce Width of the pedestrian crossing	5 m
Dolžina vpadnice (izbrana) Length of entrance road (chosen)	Krak/Arm A – 45 m, Krak/Arm B – 77 m, Krak /Arm C – 60 m.
Dolžina prehoda za pešce Length of pedestrian crossing	12 m

Kinematični vhodni podatki ***Kinematics input data***	
Pospešek a_{MV1} motornega vozila na uvozu Acceleration a_{MV1} of a motorised vehicle on the entry	1 m/s^2
Hitrost v_{MV1} motornega vozila na kraku (vpadnici) Velocity v_{MV1} of a motorised vehicle on the arm	40 km/h
Hitrost v_{MV2} motornega vozila v bližini prehoda za pešce Velocity v_{MV2} of a motorised vehicle near the pedestrians' crossing	20 km/h
Pospešek a_{PK} pešca in kolesarja Acceleration a_{PK} of a pedestrian and a cyclist	0,3 m/s^2
Hitrost v_{PK} pešca in kolesarja Velocity v_{PK} of a pedestrian and a cyclist	5 km/h

S štetjem pridobljeni podatki so vhodni podatki za prometni tok motornih vozil ter pešcev in kolesarjev v simulacijskem modelu. Ker so bile meritve izvedene v obliki štetja v posameznem kraku krožišča, predpostavljamo, da se prometni tok motornih vozil ter pešcev in kolesarjev ujema s Poissonovo porazdelitvijo. V tem primeru so časi med prihodoma dveh zaporednih motornih vozil ter pešcev in kolesarjev podani po *eksponentni* porazdelitvi. Za konkretni primer kraka A v časovnem koraku od 10^{10} do 10^{15} obsega prometni tok motornih vozil 43 enot, kar pomeni, da v krak A prihajajo motorna vozila v povprečju vsakih 6,98 sekunde, porazdeljena po *eksponentni* statistični porazdelitvi.

Experimentally acquired input data represent the input data for the traffic flow of motorised vehicles, pedestrians and cyclists in a simulation model. Since the measurements were taken in the form of counting on an individual arm of the roundabout, the presumption has been made that the traffic flow of motorised vehicles, pedestrians and cyclists matches with Poisson's statistical distribution. In this case the times between the arrivals of two consecutive motorised vehicles, pedestrians and cyclists are distributed according to the exponent distribution. For example, on arm A in the time interval from 10^{10} to 10^{15} the traffic flow of motorised vehicles consists of 43 units, which means that motorised vehicles arrive into the arm A on average every 6.98 seconds, and are distributed according to the exponent statistical distribution.

3.2 Mikrosimulacijski model krožišča

Na podlagi obravnavanega krožišča na Koroški ulici v Mariboru smo izdelali simulacijski model krožišča (sl. 5). Simulacijski model je v

3.2 Micro-simulation model of a roundabout

Based on the treated roundabout in Koroška Street in Maribor a simulation model was created (Figure 5). The simulation model in the programming

Preglednica 2. *Meritve MV ter P in K za posamezno konično uro*
Table 2. *Measurements of MV, P and C for an individual rush-hour*

Časovni korak (minute) Time interval (minutes)	**Krak A** **Arm A**		**Krak B** **Arm B**		**Krak C** **Arm C**	
	Konična ura Rush-hour 10^{10} do/to 11^{10}		Konična ura Rush-hour 14^{50} do/to 15^{50}		Konična ura Rush-hour 14^{30} do/to 15^{30}	
	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)	MV ($1/\lambda$)	P in K P and C ($1/\lambda$)
00^{00} do/to 05^{00}	43 (6,98)	6 (50,00)	58 (5,17)	44 (6,82)	53 (5,66)	48 (6,25)
05^{00} do/to 10^{00}	37 (8,11)	6 (50,00)	51 (5,88)	53 (5,66)	63 (4,76)	39 (7,69)
10^{00} do/to 15^{00}	62 (4,84)	14 (21,43)	69 (4,35)	47 (6,38)	73 (4,11)	28 (10,71)
15^{00} do/to 20^{00}	64 (4,69)	10 (30,00)	56 (5,36)	49 (6,12)	64 (4,69)	28 (10,71)
20^{00} do/to 25^{00}	58 (5,17)	9 (33,33)	57 (5,26)	33 (9,09)	51 (5,88)	18 (16,67)
25^{00} do/to 30^{00}	79 (3,80)	9 (33,33)	63 (4,76)	51 (5,88)	73 (4,11)	37 (8,11)
30^{00} do/to 35^{00}	43 (6,98)	8 (37,50)	57 (5,26)	42 (7,14)	63 (4,76)	46 (6,52)
35^{00} do/to 40^{00}	53 (5,66)	9 (33,33)	55 (5,45)	39 (7,69)	47 (6,38)	42 (7,14)
40^{00} do/to 45^{00}	63 (4,76)	10 (30,00)	49 (6,12)	43 (6,98)	46 (6,52)	81 (3,70)
45^{00} do/to 50^{00}	68 (4,41)	10 (30,00)	61 (4,92)	47 (6,38)	64 (4,69)	36 (8,33)
50^{00} do/to 55^{00}	53 (5,66)	10 (30,00)	55 (5,45)	29 (10,34)	58 (5,17)	54 (5,56)
55^{00} do/to 60^{00}	48 (6,25)	4 (75,00)	73 (4,11)	38 (7,89)	67 (4,48)	36 (8,33)

programskem orodju AutoMod [13] ponazorjen z zveznimi transporterji, po katerih poteka prometni tok motornih vozil ter pešcev in kolesarjev. Pri izdelavi simulacijskega modela smo izhajali iz dejanskih geometrijskih podatkov in kinematičnih veličin (preglednica 1), kakor tudi iz vzorca toka pešcev in motornih vozil za vse krake krožišča in prehode za pešce (preglednica 2).

Delovanje simulacijskega modela krmili programska koda (sl. 7 (a) in (b)), ki sledi algoritmu poteka na sliki 6.

Simulacija se prične s postopkom, ki na podlagi določenih funkcij v programski kodi zažene delovanje krožišča. Del primera prihoda motornih vozil v krak A, v programski kodi orodja AutoMod [14], je prikazan na sliki 7 (a) za prihod motornih vozil in 7 (b) za izvedbo pogoja o prednosti pešcev in kolesarjev.

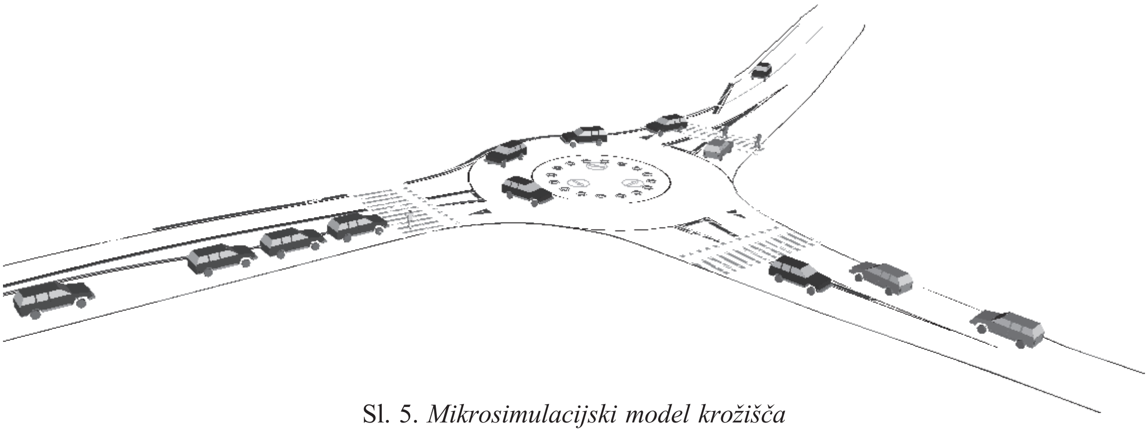
Ko je vrednost funkcije »*inicirati začetek izvajanja simulacije*« enaka »je enako«, se začne izvajati postopek »*p_stari_most_avtomobili*«. Postopek je sestavljen iz projektnih spremenljivk

tool AutoMod [14] is illustrated with connection transporters, on which the motorised vehicles', pedestrians' and cyclists' traffic flow is moving. The simulation model was created from the actual geometrical data and the kinematics values (Table 1), as well as from a sample of traffic flow of pedestrians and motorised vehicles on all the roundabout's arms and all the pedestrian crossings (Table 2).

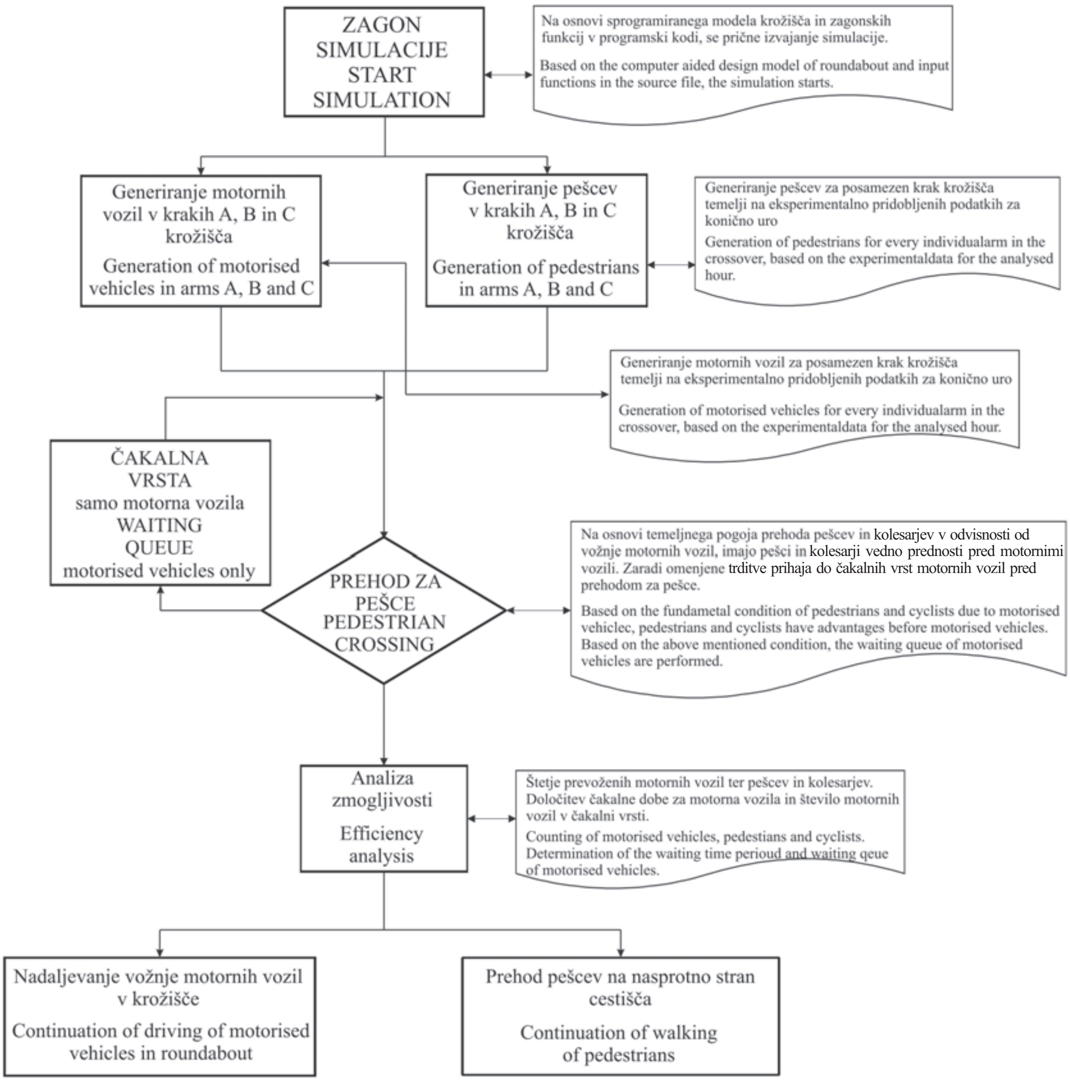
The operation of the simulation model is governed by a program code (Figure 7 (a) and (b)), following the algorithm of the course in Figure 6.

The simulation begins with a process that is based on determined functions in the program code that start the operation of a roundabout. An example of generating the arrival of motorised vehicles into the arm A in the AutoMod [14] programming tool is shown in Figure 7 (a) and in Figure 7 (b) for the implementation of the condition of pedestrians' and cyclists' priority.

When the function »begin model initialization function« equals »true«, the process »p_old_bridge_vehicles« begins. The process consists of project variables and individual program



Sl. 5. *Mikrosimulacijski model krožišča*
Fig. 5. *Micro-simulation model of a roundabout*



Sl. 6. *Algoritem poteka delovanja simulacijskega modela krožišča*
Fig. 6. *Algorithm of the course of operating the simulation model of a roundabout*

```
begin model initialization function
        create 1 load of type L_dummy_1 to p_stari_most_avtomobili
        return true
end


begin p_stari_most_avtomobili arriving procedure
while 1=1 do
        begin
                set V_set_1 to 1
                print "V_set_zacetni_1 = " V_set_1 to message

        while 1=1 do
        begin
                if V_set_1 <= 43 then wait for exponential 6.98
                else
                if V_set_1 <= 79 then wait for exponential 8.11
                else
                if V_set_1 <= 141 then wait for exponential 4.84
                .
                .
                .

        clone 1 load to p_vkrozisce_starimost_avtomobili nlt L_stari_most_avtomobili
                set V_set_1 = V_set_1 + 1
                print "V_set_1 = " V_set_1 to message
                if V_set_1 = 1000 then
                        begin
                                print "Ran out of data" to message
                                terminate
                        end
                end
        end
end
```

(a)

```
begin p_vkrozisce_starimost_avtomobili arriving procedure
        move into conv:sta_1
        inc V_stevilo_avtomobilov by 1

        set A_INSYSTEM to ac
        print "Stevilo avtomobilov = " V_stevilo_avtomobilov to message
        print "A_INSYSTEM = " A_INSYSTEM to message
        travel to conv:sta_2
        travel to conv:sta_3

        if B_block_1 current claims <> 0 then begin
                wait to be ordered on Ol_WaitForPath_1
        end

        travel to conv:sta_4

        decrement V_stevilo_avtomobilov by 1
        set A_cakalni_cas to (ac - A_INSYSTEM)
        set V_cakalni_cas to A_cakalni_cas

        print V_stevilo_avtomobilov to "ZAST.txt"
        print V_cakalni_cas to "TIME.txt"

        print "Trenutno stevilo avtomobilov pred prehodom = " V_stevilo_avtomobilov to message
        print "Cakalni cas avtomobila = " A_cakalni_cas to message

        inc V_stevilo_prevozenih_avtomobilov by 1
        print "Stevilo prevozenih avtomobilov = " V_stevilo_prevozenih_avtomobilov to message

        send to p_izkrozisca_kolosej

end
```

(b)

Sl. 7. *Primer programske kode: (a) za prihod motornih vozil - krak A (b) za izvedbo pogoja o prednosti pešcev in kolesarjev*

Fig. 7. *An example of the program code: (a) for generating motorised vehicles into arm A (b) for the implementation of the condition of pedestrians' and cyclists' priority*

in posameznih programskih zank, ki simulirajo prihod motornih vozil v odvisnosti od povprečne vrednosti prihoda v posameznem časovnem koraku petih minut in predpisane statistične porazdelitve. Simulacija se ustavi po preteku predpisanega časa, tj. ene ure. Dotok preostalega prometnega toka motornih vozil ter pešcev in kolesarjev je programirano podobno, glede na eksperimentalno pridobljene vrednosti, predstavljene v preglednici 2. Upoštevali smo, da so prihodi motornih vozil ter pešcev in kolesarjev neenakomerni, zato smo za dotok uporabili *eksponentno* statistično porazdelitev. Pri izdelavi glavne programske logike krožišča smo izhajali iz splošno veljavnega pogoja, da imajo pešci in kolesarji zmeraj prednost pred motornimi vozili.

Algoritem (sl. 6) pri prihodu motornega vozila do obravnavanega prehoda za pešce preveri, ali je na prehodu za pešce že pešec ali kolesar. V primeru, da je na prehodu za pešce pešec ali kolesar »*B_trenutna zahteva pogoja "omejitev" - zapore <> 0*«, se motorno vozilo nemudoma ustavi in čaka, da pešec zapusti prehod »*čakaj na vrstni red Ol_čakaj na pot_1*«. Kadar je prometni tok pešcev

loops that simulate the arrival of motorised vehicles depending on the average arrival value in an individual time interval of 5 minutes and the directed statistical distribution. After the defined time interval, i.e., one hour, the simulation is stopped. Generating of the rest of the traffic flow of motorised vehicles, pedestrians and cyclists is programmed similarly, according to the experimentally acquired values, presented in Table 2. It is presumed that the arrivals of the motorised vehicles, pedestrians and cyclists are uneven, so the exponent statistical distribution has been used for generating the traffic flow. When creating the main program logic of a roundabout the general valid condition was presumed, that pedestrians and cyclists have priority with regard to the motorised vehicles.

The algorithm (Figure 6) for the arrival of a motorised vehicle to the considered pedestrian crossing verifies whether there is already a pedestrian or a cyclist on the pedestrian crossing or not. In the case that there is a pedestrian or a cyclist on the pedestrian crossing »*B_block_1 current claims <> 0*«, the motorised vehicle immediately stops and waits until the pedestrian leaves the crossing »*wait to be ordered on Ol_waithForPath_1*«. When the pedestrians' or cyin kolesarjev močno izrazit, prihaja do čakalnih vrst motornih vozil (sl. 8 (a) in (b)).

V trenutku, ko je prehod za pešce sproščen »*B_trenutna zahteva pogoja “omejitev“ - zapore = 0*«, nadaljujejo motorna vozila po zaporedju FIFO svojo vožnjo. Vožnja motornih vozil poteka neovirano tako dolgo, dokler se na prehodu ne pojavi naslednji pešec ali kolesar, ki ponovno »ustavi« vožnjo motornih vozil.

Za vsako prevoženo motorno vozilo, pešca in kolesarja zapisuje algoritem (slika 6) osnovne podatke »*V_cakalni_cas* in *V_stevilo_avtomobilov*«, in sicer: število prevoženih motornih vozil ter število prehodov pešcev in kolesarjev, koliko časa je bilo posamezno motorno vozilo na izbranem kraku krožišča (čakalna doba) in ali je bilo posamezno motorno vozilo v čakalni vrsti.

Na podlagi simulacijske analize želimo ugotoviti, ali je glede na eksperimentalno izmerjene podatke zmogljivost krožišča v posameznih krakih še sprejemljiva v odvisnosti od (*i*) čakalne dobe in (*ii*) čakalne vrste motornih vozil pred prehodom za pešce.

3.3 Analiza rezultatov mikrosimulacije krožišča

Rezultati opravljene analize za določitev čakalne dobe in čakalne vrste motornih vozil v odvisnosti od prometnega toka pešcev in kolesarjev podajajo poglavitne sklepe, ki so predstavljeni v diagramih (a do f) na sliki 9. Simulacijska analiza je bila izvedena na podlagi znanih geometrijskih veličin krožišča in izbranih kinematičnih veličin za motorna vozila ter pešce in kolesarje.

clists’ flow is extremely strong, waiting lines of motorised vehicles occur (Figure 8 (a) and (b)).

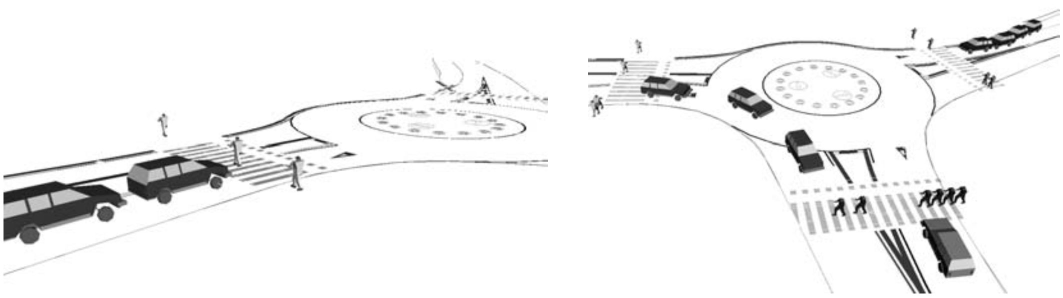
The moment the pedestrian crossing is free »*B_block_1 current claims = 0*«, motorised vehicles continue with driving in the FIFO consequence according to their drive. The driving of motorised vehicles takes place until the next pedestrian or cyclist appears on the crossing, which again stops the driving of the motorised vehicles.

For every passing motorised vehicle, pedestrian or a cyclist the algorithm registers (Figure 6) the basic information »*V_waiting_time in V_number_of motorised vehicles*« as follows: the number of passing motorised vehicles and the number of pedestrians’ or cyclists’ crossings in the roundabout, how long an individual motorised vehicle has been in the chosen arm of the roundabout (the waiting period) and if an individual motorised vehicle has been in a queue (waiting line).

The main goal of the simulation analysis is to establish the capacity of the roundabout on individual arms depending on (*i*) the waiting period and (*ii*) if the waiting line of motorised vehicles in front of a pedestrian crossing is still acceptable, according to the experimentally measured information.

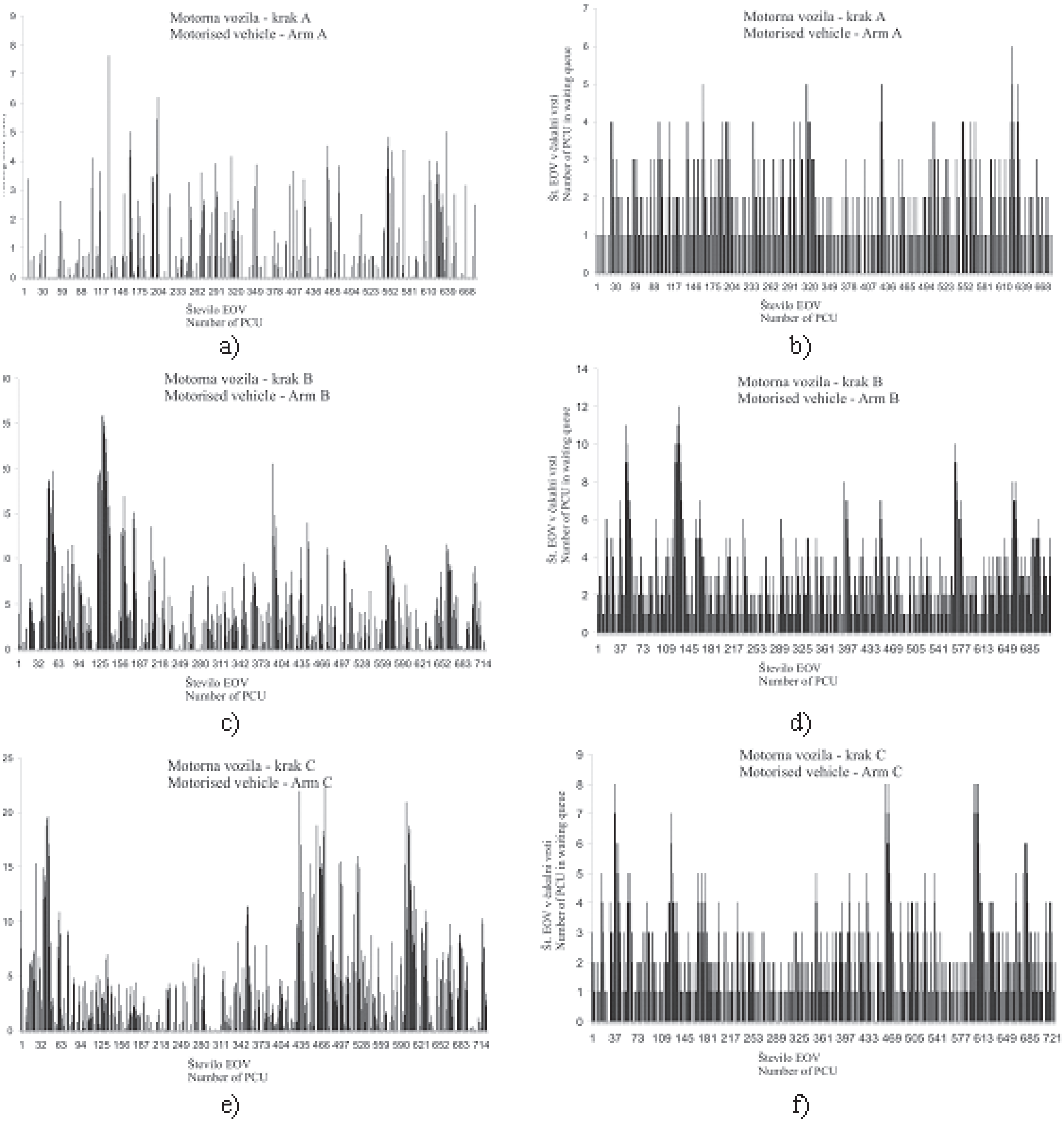
3.3 An analysis of the results of the micro-simulation of a roundabout

The results of the performed analysis for determining the waiting period and the waiting line of motorised vehicles depending on the pedestrians’ and cyclists’ traffic flows give basic conclusions, presented in the diagrams (a to f) in Figure 9. The simulation analysis was performed based on the geometrical values of a roundabout and the kinematics values for motorised



(a) (b)

Sl. 8. *Primer čakalne vrste motornih vozil zaradi toka pešcev*
Fig. 8. *An example of a waiting line of motorised vehicles because of pedestrians’ flow*



Sl. 9. *Rezultati analize prometnega toka motornih vozil z vidika čakalne dobe (a, c, e) ter čakalne vrste (b, d, f) v odvisnosti od prometnega toka pešcev in kolesarjev*

Fig. 9. *The results of the analysis of the traffic flow of the motorised vehicles considering the waiting period (a, c, e) and the waiting line (b, d, f) depending on the pedestrians' and cyclists' traffic flows*

Na sliki 9 lahko vidimo porazdelitev čakalne dobe (a, c, e) in čakalne vrste (b, d, f) motornih vozil v krožišču. Rezultati analize kažejo, da se število prevoženih motornih vozil ter število prehodov pešcev in kolesarjev, glede na izbrano konično uro, zelo dobro ujemata z eksperimentalno pridobljenimi podatki (preglednica 3).

Glede na porazdelitev čakalne dobe (sl. 9 a, c in e) za motorna vozila, lahko vidimo

The distribution of the waiting period (a, c, e) and the waiting line (b, d, f) of motorised vehicles in a roundabout is presented in Figure 9. The results of the analysis show that the number of passing motorised vehicles and the number of passing pedestrians and cyclists, according to the selected rush-hour, matches well with the experimentally gathered results (Table 3).

According to the waiting-period distribution (Figures 9 a, c and e) for motorised vehicles, proporsorazmerno majhne vrednosti za posamezne krake krožišča. Opazimo lahko, da so čakalni časi v kraku A najkrajši, saj je v omenjenem kraku pretok pešcev in kolesarjev najmanjši (krak A leži na južnem delu krožišča in ponazarja del Starega mostu). Glede na sorazmerno večji pretok pešcev in kolesarjev v krakih B in C, so posledično čakalne dobe večje, vendar ne presegajo največjega čakalnega časa 35 sekund.

V odvisnosti od čakalnih vrst (slika 9 b, d in f) za motorna vozila lahko opazimo sorazmerno majhne vrste. Zopet se pojavljajo najmanjše čakalne vrste v kraku A (največ 6 motornih vozil), sledi krak C (največ 10 motornih vozil) in krak B (največ 11 motornih vozil). Poudariti je treba, da se pojavijo čakalne vrste, poleg zastoja v krožišču zaradi vpliva pešcev in kolesarjev, tudi zaradi prometnega toka motornih vozil z *eksponentno* statistično porazdelitvijo. Slednje pomeni, da se lahko v poljubnem kraku hkrati pojavi večje število motornih vozil, ki v odvisnosti od obremenitve v krožišču povzročijo zastoj in posledično čakalno vrsto.

4 SKLEPI

V tem prispevku je analiziran vpliv prometnega toka pešcev na prepustno zmožnost, tj. zmogljivost enopasovnega krožišča z uporabo diskretnih numeričnih simulacij. Najpomembnejši cilj opravljene analize je bil ugotoviti resnične parametre, ki so kasneje uporabljeni pri določanju vpliva toka pešcev na zmogljivost načrtovanega krožišča.

V prvem vsebinskem sklopu prispevka so predstavljena glavna teoretična izhodišča pri analiziranju prometnega toka motornih vozil ter pešcev in kolesarjev v krožišču. V krožiščih je tok pešcev prednosten, zato mu vozila na uvozih/

tionally low values for the individual arms of the roundabout are obvious. The waiting times in arm A are the shortest, since in the mentioned arm the pedestrians' and cyclists' flows are the smallest (arm A is located in the south part of the roundabout and represents a part of the Old bridge). According to the proportionally larger flow of pedestrians and cyclists in the arms B and C, consequentially the waiting periods are longer, but do not exceed the maximum waiting time of 35 seconds.

Due to the waiting lines (Figures 9 b, d and f) for motorised vehicles, proportionally smaller queues can be seen. Again, the smallest waiting lines occur in the arm A (a maximum of 6 motorised vehicles), the next is arm C (a maximum of 10 motorised vehicles) and the arm B is last (a maximum of 11 motorised vehicles). It should be emphasized that waiting lines (next to the roundabout blockage due to pedestrians' and cyclists' flows) occur due to the traffic flow of motorised vehicles with an exponent statistical distribution as well. This means that in any optional arm of the roundabout there can be a larger number of motorised vehicles, which depending on the traffic load in the roundabout cause congestion and consequently a waiting line.

4 CONCLUSIONS

The influence of the pedestrians' traffic flow, i.e., the capacity of a one-lane roundabout using discrete numeric simulations is presented. The most important goal of the performed analysis was to establish the real parameters that were later used for determining the influence of pedestrians' traffic flow on the capacity of the foreseen roundabout.

In the first part of the present work the main theoretical background for the analysis of traffic flow of motorised vehicles, pedestrians and cyclists in a roundabout is presented. Since in roundabouts the pedestrian traffic flow has priority, the vehicles on

Preglednica 3. *Primerjava rezultatov meritev in simulacijske analize*
Table 3. *Comparison of the results of measuring and the simulation analysis*

	Krak A Arm A		Krak B Arm B		Krak C Arm C	
	MV	P in K P and C	MV	P in K P and C	MV	P in K P and C
Meritve Measuring	671	105	704	515	722	493
Simulacija Simulation	683	100	719	513	725	492
Odstopek Discrepancy	-1,79 %	4,76 %	-2,13 %	0,39 %	-0,42 %	0,20 %

izvozih morajo odstopiti prednost. Pri tem prihaja do motenj pri uvažanju/izvažanju toka motornih vozil, tok motornih vozil je oviran. Bolj, ko je tok motornih vozil oviran, manjša je prepustna zmožnost krožišča. V primeru, da so ovirani tokovi na uvozu v krožišče, se lahko zgodi, da ni dosežena niti najmanjša zmogljivost. V primeru, da so ovirani tokovi na izvozu iz krožišča, se lahko zgodi, da je presežena največja zmogljivost. V dejanskih razmerah sta uvozni in izvozni tok ovirana hkrati, zastoji se prenašajo s kraka na krak, v smeri gibanja urnega kazalca. V prispevku je pri analizi vpliva toka pešcev na prepustno zmožnost krožišča uporabljeno matematično modeliranje prometnih tokov z uporabo metode diskretnih simulacij, upoštevaje statistično ovrednotene vhodne podatke za prometna toka motornih vozil in pešcev.

Analitični model posameznega kraka krožišča je predstavljen s teorijo čakalnih vrst. Pomanjkljivost omenjene teorije je v omejenosti na poenostavljene modele, medtem ko je predstavljeni model krožišča s številnimi medsebojnimi odvisnostmi motornih vozil ter pešcev in kolesarjev preveč zapleten. Analitični modeli zaradi poenostavitev ne zagotavljajo dovolj velike natančnosti in so samo približek dejanskemu stanju. Zaradi omenjene pomanjkljivosti smo uporabili tehniko diskretnih numeričnih simulacij.

V drugem vsebinskem sklopu je predstavljena diskretna numerična simulacija s simulacijskim modelom krožišča. Simulacijski model krožišča je splošen, kar pomeni da ga lahko razširimo za vsako posamezno izvedbo, glede na izbrane geometrijske in kinematične veličine. Matematični model izhaja iz zakonitosti sprejemljivih časovnih praznin v prometnem toku pešcev, ki jih uporabljajo vozila za uvažanje/izvažanje iz krožišča. Za definiranje prometnega toka motornih vozil ter pešcev in kolesarjev smo uporabili dejanske vhodne podatke za vse cestne krake in prehode za pešce, ki smo jih dobili s štetjem prometa na Koroški ulici v Mariboru. Ugotovili smo, da se rezultati meritev in simulacijske analize dobro ujemajo, kar pomeni, da so rezultati simulacijske analize dobra napoved za ovrednotenje čakalne dobe in čakalnih vrst motornih vozil v posameznem kraku krožišča. Glede na porazdelitev čakalne dobe in posledično čakalnih vrst v odvisnosti od števila prevoženih motornih vozil, lahko vidimo, da so

entries/exits have to give way to pedestrians. During this disturbances to the entering/exiting of motorised vehicles occur, and the motorised vehicles' flow is disturbed. The more disturbed the motorized vehicles' flow is, the lower is the capacity of the roundabout. In the case the flows towards an entry to the roundabout are disturbed, the minimum capacity is not reached. In the case the flows towards an exit from the roundabout are disturbed, the maximum capacity can get exceeded. In real conditions, the entering and the exiting motorised traffic flows are disturbed simultaneously, and the congestions are transferred from arm to arm, in a clockwise direction. For this purpose, the mathematical modelling of traffic flows with the use of discrete simulations has been used for the analysis of the influence of pedestrians' flow on the capacity of the roundabout, considering the statistically evaluated input data for the motorised vehicles' and pedestrians' traffic flows.

The analytical model of an individual arm of a roundabout is presented with the waiting-line (queue) theory. The drawback of the mentioned theory is in its limitations with simplified models, while the presented model of a roundabout, with many mutual dependencies between the motorised vehicles, pedestrians and cyclists is too complex. Due to simplifications, the analytical models do not ensure sufficient accuracy and present only an approximation of the actual situation. Because of these drawbacks the discrete numerical simulations technique was used.

In the second part, a discrete numerical simulation of a roundabout is presented. The simulation model of a roundabout is general, which means 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 pedestrians' traffic flow, used by the vehicles for entering/exiting a roundabout. For a determination of the traffic flow of motorised vehicles, pedestrians and cyclists the real input data for all the roundabout's arms and pedestrian crossings, acquired by the traffic counting on Koroška Street in Maribor were used. The results of the measurements and simulation analyses match well, which means that the simulation analysis results give a good prediction for the evaluation of the waiting period and the waiting lines of motorized vehicles in an individual arm of the roundabout. According to the waiting-period distribution and consequentially the waiting lines depending on the number of motorised vehicles one can determine that the waiting periods and the queue of motorized vehičakalni časi in vrste motornih vozil sorazmerno majhne. Ugotovljeno odvisnost lahko komentiramo z dejstvom, da bi načrtovano krožišče ustrezalo načrtovani zmogljivosti in ne bi prihajalo do čezmernih čakalnih časov in čakalnih vrst motornih vozil.

Simulacijski model, prikazan v prispevku, ni le znanstveni postopek matematičnega modeliranja krožišč, temveč pomeni tudi praktično metodo pri odločanju o smiselnosti izvedbe krožišča v primeru velikega števila pešcev.

V nadaljnjih raziskavah bi bilo primerno dograditi prvotni preprosti model za celotni krak krožišča, vključno z vplivom krožečega toka na krožišču, predvideti različne hitrosti pešcev in njihov prihod v večjem številu vrst.

cles are proportionally low. The established dependency can be commented with the fact that the foreseen roundabout is going to suit the expected capacity and excessive waiting periods and waiting lines of motorized vehicles will not occur.

However, the simulation model presented in this paper does not only present a scientific approach to mathematical modelling of roundabouts, but also presents a practical method for deciding on the suitability of introducing a roundabout in the case of a large number of pedestrians.

For future research it would be sensible to upgrade the present simple model for all the arms of a roundabout, including the influence of the circular flow on the circular roadway, considering different pedestrian speeds and their arrival in more than single file.

5 OZNAKE
5 SYMBOLS

dejanska zmogljivost prometnega toka motornih vozil ter pešcev in kolesarjev	λ	actual capacity of traffic flow of motorized vehicles, pedestrians and cyclists
največja zmogljivost prometnega toka motornih vozil ter pešcev in kolesarjev	μ	maximum capacity of traffic flow of motorized vehicles, pedestrians and cyclists
izkoristek posameznega kraka krožišča	ρ	utilization rate an individual arm of a roundabout intersection
časovni korak	t	time interval
porazdelitvena funkcija	$F(t)$	distributional function,
gostota verjetnosti	$f(t)$	probability density,
Poissonova porazdelitev števila prihodov motornih vozil, pešcev in kolesarjev na časovno enoto	M	Poisson's distribution of the number of arrivals of motorized vehicles, pedestrians and cyclists in a time unit,
stalnica oz. deterministična porazdelitev časa, ki je potreben za vožnjo motornih vozil mimo prehoda za pešce ter prehoda pešcev in kolesarjev	D	constant or deterministic distribution of the time, required for driving of motorized vehicles by pedestrians' crossing and the pedestrians' and cyclists' crossing,
število strežnih mest v sistemu čakalne vrste (v našem primeru se navezuje na prehod za pešce)	s	number of serving stations in a waiting line system (in our case regarding the pedestrians' crossing),
prihod v sistem je določen z neskončnim tokom motornih vozil ter pešcev in kolesarjev	∞	arrival to the system is determined by an infinite flow of motorized vehicles, pedestrians and cyclists,
sistem omogoča neskončno mnogo voženj motornih vozil preko prehoda za pešce ter prehodov pešcev in kolesarjev na drugo stran cestišča	∞	system enables infinite number of driving of motorized vehicles over a pedestrian crossing and pedestrians' and cyclists' crossings to the other side of the road,
enota (motorno vozilo, pešec ali kolesar), ki pride v sistem prva, je tudi prva postrežena	$FIFO$	unit (motorized vehicle, pedestrian or cyclist) that comes first into the system is first served,
hitrost motornega vozila na vpadnici	v_{MV1}	velocity of a motorized vehicle on an entrance road,
hitrost motornega vozila v bližini peš-cone	v_{MV2}	velocity of a motorized vehicle near a walking-zone,

hitrost pešca in kolesarja	v_{PK}	velocity of pedestrian and cyclist,
pospeševanje motornega vozila na vpadnici	a_{MV1}	acceleration of a motorized vehicle on an entrance road,
pospeševanje pešca in kolesarja	a_{PK}	acceleration of pedestrian and cyclist,
enota motornega vozila	EOV/ PCU	personal car unit
motorna vozila	MV	motorised vehicles
pešci	P	pedestrians
kolesarji	K/C	cyclists

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