MLADEN KALAJŽIĆ, B. Sc.
MORH, Pilotska škola Zadar
VP 3049, 23000 Zadar, Republika Hrvatska
KATICA MILOŠ, D. Sc.
Fakultet prometnih znanosti
Vukelićeva 4, 10000 Zagreb, Republika Hrvatska
MIRELA MUIĆ, B. Eng.
Institut prometa i veza
Kušlanova 2, 10000 Zagreb, Republika Hrvatska

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SIMULATION MODEL OF TRAFFIC JAMS AT CROSSROADS

ABSTRACT

Traffic congestion is one of the major problems in most cities. It is the consequence of unavoidable motorization, but also, in many cases, of improper solutions considering construction of roads or organisation of traffic.

This paper deals with one problematic crossroad in the town of Zadar in which traffic jams occur due to poor organisation of traffic. Using mathematical simulation, the first part proves that traffic jams will certainly occur, and in the second part, crossroads signalling is considered as a possible solution which, if combined with intelligent control could significantly improve the organisation of traffic at this crossroads.

KEY WORDS

traffic jam, simulation, signalling

1. INTRODUCTION

Traffic jams in big cities are one of the burning questions concerning urban and traffic planning as well as organization of life and work in them. Smaller cities are not faced with that problem to such an extent, but there are periods of time when traffic jams occur as well. These holdups occur in the traffic peaks closely related to the arrivals to and departures from the work places as well as shopping and weekend trips.

Moreover, traffic problematic can be observed concerning the parts of the year, which is of great importance to the developed tourist centers, the traffic capacities of which should have such dimensions that they could accommodate the waves of motorised tourists. Unfortunately, while designing and building of roads there was often no concern taken for the everyday life, let alone the tourist season. The example is illustrative for such an approach.

The town of Zadar with around 80,000 inhabitants is a middle-size city according to Croatian standards and a centre of highly receptive tourist region. Traffic is not ideally organised due to the complexity of its development into an urban centre. The historical core of the town is situated on the peninsula where the traffic flows in a circle, conditioned by the walls, and even though there is an acute problem of parking spaces it is a satisfactory solution. Due to the inflow of inhabitants, the town has spread to the land involving nearby communities. As the town developed, so did the roads.

In most cases traffic planning was in the function of physical planning or better yet, road construction followed the construction of residential and business buildings and neighbourhoods, and in a small number of cases the traffic experts had been consulted before the building of an object of any kind. On the other hand, at places where the road construction was performed systematically, the problem of traffic organisation occurred.

Crossroads, which is the topic of this paper, has no such lacks in planning and realisation, but rather in traffic organisation, which is most probably the consequence of uncontrolled city development.

Traffic jams are undesired because of:

- higher fuel consumption,
- increased pollution due to exhaust gases as well as noise,
- a whole number of losses that come out in the form of work failures, decrease of work capacity caused by frustration of queuing, etc.

Holdups are counterproductive from the aspect of safety as well, for people lose their patience very quickly and try the impossible in order to cut the time they spend on waiting.

The goal of this paper is to point out the problem and suggest a possible solution, with the purpose of stimulating quality consideration for the traffic organisation in the cities.

2. DESCRIPTION OF THE PROBLEM

The mentioned crossroads is situated in part of the town called Voštarnica on the Ban Jelačić and J. J. Strossmayer streets. The crossroads is entered from three entrances with six traffic directions.

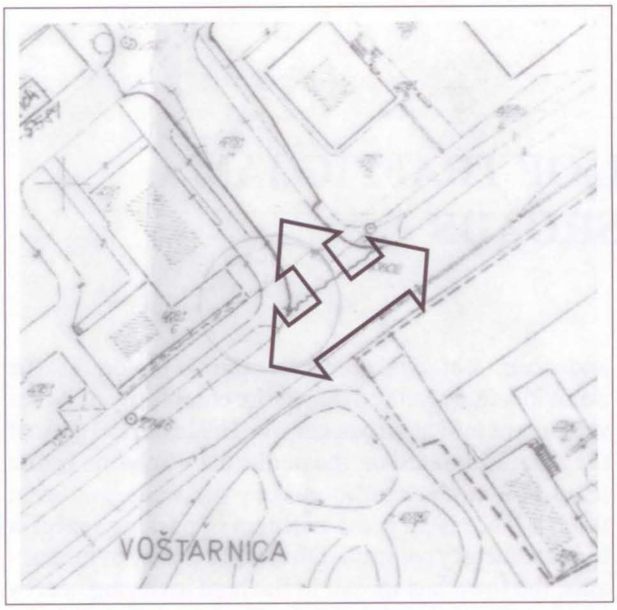


Figure 1a

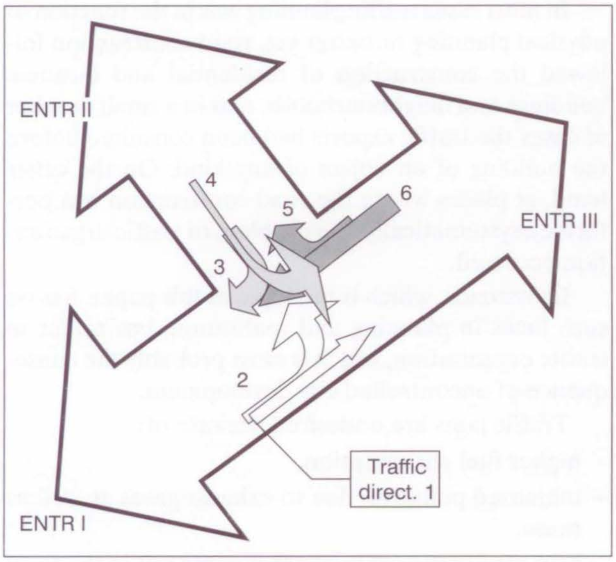


Figure 1b

Traffic flows in such a way that directions 1 and 2 have absolute priority, followed by directions 3 and 4 and then 5 and 6. Vehicles enter the crossroads from three entrances randomly and completely independently. The moments of arrival of a single vehicle make the flow of events that with certain tolerances represent a simple Poisson flow of events. Naturally, the requirement of ordinariness for every new-coming vehicle is satisfied, because only one vehicle can pass through the crossroads, especially since individual directions will be considered as individual flows. The flows will be stationary during "recording" times, which means during daily peaks of traffic (to and from work), but the lack of consequences could be argued, and this will be clearer from Figure 2.

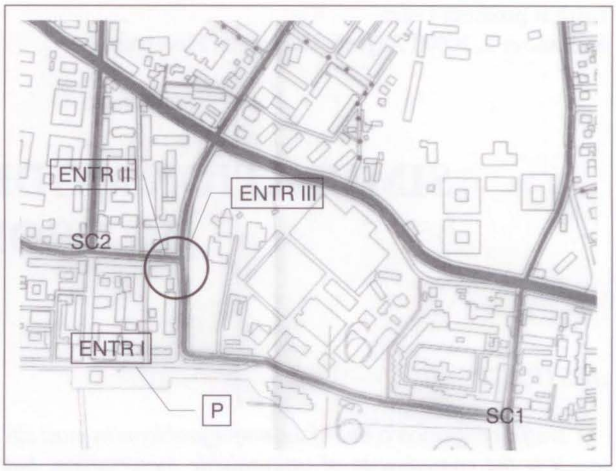


Figure 2

Arrivals of vehicles from the entrance **I** are determined by the signal controlled crossroads (**SC1**) as the primary source, and the parking lot (**P**) as the secondary one. However, the distance between the traffic lights is such that we can talk about random times of arrival from entrance **I**.

Entrances **II** and **III** are exclusively related to the signal controlled crossroads (**SC2** and **SC3**) but in these two cases the distance is smaller than the previous problematic one. This distance determines the capacity of the queues on entrances **II** and **III**. But considering the fact that the vehicle arrivals to both signal controlled crossroads are random, it can be approximated that arrivals to the problematic crossroads are random too, so that the condition regarding the lack of consequences is fulfilled.

The mentioned queuing capacity is determined on the basis of the distance from the previous to the conflicting crossroads, with an average 4m vehicle length and 1m distance between two vehicles. The calculated capacity amounted to nine vehicles for the entrance **II** and 30 vehicles for the entrance **III**.

3. SIMULATION

Considering the fact that the observed crossroads is a system of relative priority, meaning that if a vehicle from the entrance **III** is already in the crossroads, vehicles from the entrances **I** and **II** have to wait until the preceding vehicle passes, the simulation is based on these aspects:

- every traffic entrance is an independent flow of events (vehicle arrivals),

- in the beginning there is one vehicle on each entrance,
- time of service (passing of a vehicle through the crossroads) is 2.5 seconds (average path travelled by a vehicle through the crossroads divided by the average speed of 30 km/h),
- all the subsequent arrivals are determined by random numbers, and for each entrance there is a different set of random numbers,
- during the first part of simulation, traffic entrances are not divided by directions, for if the vehicle from entrance **I** wants to continue its movement in the direction 1 or 2, and there are already vehicles from entrance **II** or **III** in the crossroads, the vehicle from entrance **I** has to wait regardless of the priority.

Random numbers used in this simulation were obtained by means of the random numbers generator that works on the principle of calculations of non-periodical noises in the atmosphere[1].

For the needs of the paper, the recording was carried out during the morning traffic peak in the time interval of 30 minutes and the following results were recorded:

- the number of vehicles from entrance I = 297 or 9.90 per minute,
- the number of vehicles from entrance II = 233 or 7.76 per minute,
- the number of vehicles from entrance III = 225 or 7.50 per minute,

with time intervals of their arrival to the crossroads:

- for entrance I, 1-10 seconds,
- for entrance II, 1-12 s,
- for entrance III, 1-12 s.

Considering the limited possibilities of recording traffic situation at a crossroads, the frequency of individual intervals has been left out and this simulation was performed in such a way that the time intervals of 1-10 s were equally assigned random numbers from 1 to 50, and the intervals of 1-12 s were assigned two independent sets of random numbers from 1 to 60. The number of served vehicles has also been left out so that the intensity of the exit flow μ has been determined by the average duration of time necessary for a vehicle to pass the crossroads, which will naturally yield only theoretical value. For the time interval of service $\tau = 2.5$ s follows $\mu = 1/\tau'$ which gives $\mu=24$ vehicles per minute, where τ' stands for time of service in minutes.

The resulting flow of simulation is shown in Table 1.

It can be seen from the Table that after 5 min and 15 s congestion develops at the entrance **III**, i.e. the 31st vehicle occurred in the queue. Due to the capacity of only 30 vehicles, the newly arrived vehicle was cancelled. The congestion, i.e. the jammed entrance (lane) is less than welcome because it prevents normal traffic flow and indicates the necessity for a signal controlled crossroads.

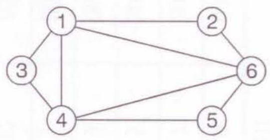
4. SIGNALIZATION OF THE CROSSROADS

In order to solve the signalization of the crossroads, the conflicting traffic directions were determined first, and then the matrix of incident was made from which the compatible phases of potential signalization were derived.

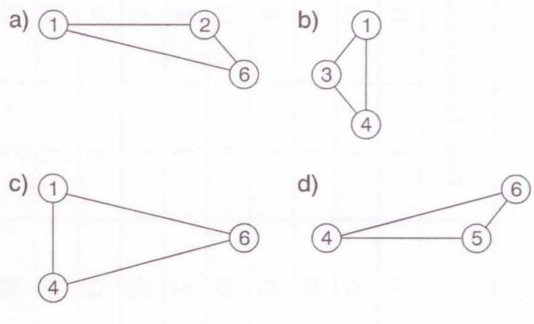
As there are 6 directions the matrix of incident is:

$$\begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

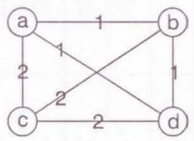
Based on the matrix, the graph of transitive states was developed:



Then the circular cycles were singled out of the graph:



Based on the above, the possible transitions were determined:



1° a – b - d - a
2° b – d – a –b
3° d – b – a – d,
where $\Sigma 1° = \Sigma 2° = \Sigma 3° = 3$

If number one solution is chosen then:

- first comes the green interval for the traffic directions 1, 2 and 3,
- then the green interval for 1, 5 and 6,
- ending with green interval for 4, 5 and 3 again.

Table 1

Number of arrival	Random numbers			Delay between succeeding arrivals			Moment of arrival (from 0 s to first arrival) [min.sec]			Order of service
	I	II	III	I	II	III	I	II	III	
1	24	55	45	5	11	9	00.05	00.11	00.09	1st minute: I(0-2.5s) II(2.5-5s) I(5-7.5s) I(7.5-10s) III(10-12.5s) I(12.5-15s) II(15-17.5s) II(17.5-20s) III(20-22.5s) I(22.5-25s) I(25-27.5s) II(27.5-30s) III(30-32.5s) I(32.5-35s) I(35-37.5s) I(37.5-40s) I(40-42.5s) II(42.5-45s) I(45-47.5s) II(47.5-50s) II(50-52.5s) I(52.5-55s) I(55-57.5s) II(57.5-60s) 2nd minute: II(0-2.5s) I(2.5-5s) III(5-7.5s) III(7.5-10s) I(10-12.5s) II(12.5-15s) I(15-17.5s) II(17.5-20s) III(20-22.5s) I(22.5-25s) III(25-27.5s) II(27.5-30s) I(30-32.5s) III(32.5-35s) I(35-37.5s) I(37.5-40s) I(40-42.5s) II(42.5-45s) II(45-47.5s) III(47.5-50s) I(50-52.5s) II(52.5-55s) III(55-57.5s) III(57.5-60s) 3rd minute: I(0-2.5s) II(2.5-5s) I(5-7.5s) I(7.5-10s) I(10-12.5s) II(12.5-15s) II(15-17.5s) I(17.5-20s) I(20-22.5s) II(22.5-25s) I(25-27.5s) II(27.5-30s) I(30-32.5s) II(32.5-35s) II(35-37.5s) II(37.5-40s) I(40-42.5s) I(42.5-45s) I(45-47.5s) II(47.5-50s) I(50-52.5s) II(52.5-55s) II(55-57.5s) II(57.5-60s)
2	10	5	33	2	1	7	00.07	00.12	00.16	
3	24	45	21	5	9	5	00.12	00.21	00.21	
4	44	53	42	9	11	9	00.21	00.33	00.30	
5	11	19	2	3	4	1	00.24	00.37	00.31	
6	32	13	56	7	3	12	00.31	00.40	00.43	
7	1	45	18	1	9	4	00.32	00.49	00.47	
8	5	49	41	1	10	9	00.33	00.59	00.56	
9	7	58	26	2	12	6	00.35	01.11	01.02	
10	44	27	6	9	6	2	00.44	01.17	01.04	
11	33	45	44	7	9	9	00.51	01.26	01.13	
12	8	33	24	2	7	5	00.53	01.33	01.18	
13	42	60	49	9	12	10	01.02	01.45	01.28	
14	40	28	55	8	6	11	01.10	01.51	01.39	
15	17	32	20	4	7	4	01.14	01.58	01.43	
16	33	1	34	7	1	7	01.21	01.59	01.50	
17	42	43	27	9	9	6	01.30	02.08	01.56	
18	11	1	58	3	1	12	01.33	02.09	02.08	
19	7	2	46	2	1	10	01.35	02.10	02.28	
20	17	32	33	4	7	7	01.39	02.17	02.35	
21	50	26	3	10	6	1	01.49	02.23	02.36	
22	42	41	46	9	9	10	01.58	02.32	02.46	
23	28	22	35	6	5	7	02.04	02.37	02.53	

Number of arrival	Random numbers			Delay between succeeding arrivals			Moment of arrival (from 0 s to first arrival) [min.sec]			Order of service
	I	II	III	I	II	III	I	II	III	
24	13	9	23	3	2	5	02.07	02.39	02.58	4^{th} minute: I(0-2.5s) II(2.5-5s) II(5-7.5s) I(7.5-10s) I(10-12.5s) II(12.5-15s) II(15-17.5s) I(17.5-20s) I(20-22.5s) II(22.5-25s) II(25-27.5s) I(27.5-30s) II(30-32.5s) III(32.5-35s) III(35-37.5s) I(37.5-40s) I(40-42.5s) II(42.5-45s) I(45-47.5s) II(47.5-50s) III(50-52.5s) III(52.5-55s) I(55-57.5s) I(57.5-60s)
25	4	58	35	1	12	7	02.08	02.51	03.05	
26	39	21	3	8	5	1	02.16	02.56	03.06	
27	14	5	18	3	1	4	02.19	02.57	03.10	
28	22	11	16	5	3	4	02.24	03.00	03.14	
29	22	37	47	5	8	10	02.29	03.08	03.24	
30	49	27	44	10	6	9	02.39	03.14	03.33	
31	12	5	5	3	1	1	02.41	03.15	03.34	
32	15	45	21	3	9	5	02.44	03.24	03.39	
33	28	13	17	6	3	4	02.50	03.27	03.43	
34	43	54	23	9	11	5	02.59	03.38	03.48	
35	41	41	10	7	9	2	03.06	03.47	03.50	
36	2	49	22	1	10	5	03.07	03.57	03.55	
37	42	54	35	9	11	7	03.16	04.08	04.02	
38	9	30	54	2	6	11	03.18	04.14	04.13	
39	36	06	22	8	6	5	03.26	04.20	04.18	
40	47	35	13	10	7	3	03.36	04.27	04.21	
41	12	20	30	3	4	6	03.39	04.31	04.27	
42	26	41	56	6	9	12	03.45	04.40	04.39	
43	41	46	25	9	10	5	03.54	04.50	04.44	
44	10	23	18	2	5	4	03.56	04.55	04.48	5^{th} minute: I(0-2.5s) I(2.5-5s) I(5-7.5s) II(7.5-10s) II(10-12.5s) I(12.5-15s) II(15-17.5s)
45	16	23	57	4	5	12	04.00	05.00	05.00	
46	3	16	39	1	4	8	04.01	05.04	05.08	

Number of arrival	Random numbers			Delay between succeeding arrivals			Moment of arrival (from 0 s to first arrival) [min.sec]			Order of service
	I	II	III	I	II	III	I	II	III	III(17.5-20s) I(20-22.5s) I(22.5-25s) I(25-27.5s) I(27.5-30s) I(30-32.5s) II(32.5-35s) II(35-37.5s) I(37.5-40s) II(40-42.5s) II(42.5-45s) III(45-47.5s) I(47.5-50s) II(50-52.5s) I(52.5-55s) I(55-57.5s) II(57.5-60s) 6th minute: II(0-2.5s) III(2.5-5s) I(5-7.5s) I(7.5-10s) II(10-12.5s) I(12.5-15s). Surfeit on the entrance III
47	6	47	6	2	10	2	04.03	05.14	05.10	
48	41	40	16	9	8	4	04.12	05.22	05.14	
49	27	10	2	6	2	1	04.18	05.24	05.15	
50	12	19	34	3	4	7	04.21	05.28	05.22	
51	9	59	35	2	12	7	04.23	05.40	05.29	
52	13	59	11	3	12	3	04.26	05.52	05.32	
53	4	1	47	1	1	10	04.27	05.53	05.42	
54	49	28	40	10	6	8	04.37	05.59	05.50	
55	46	32	16	10	7	4	04.47	06.06	05.54	
56	24	23	21	5	5	5	04.52	06.11	05.59	
57	2	22	60	1	5	12	04.53	06.16	06.11	
58	48	9	37	10	2	8	05.03	06.18	06.19	
59	1	2	34	1	1	7	05.04	06.19	06.26	
60	38	51	38	8	11	8	05.12	06.30	06.34	
61	31	14	50	7	3	10	05.19	06.33	06.44	
62	28	12	25	6	3	5	05.25	06.36	06.49	
63	31	43	43	7	9	9	05.32	06.45	06.58	
64	49	44	41	10	9	9	05.42	06.54	07.07	
65	9	57	36	2	12	8	05.44	07.06	07.15	
66	40	23	7	8	5	2	05.52	07.11	07.17	
67	19	26	59	4	6	12	05.56	07.17	07.29	
68	7	60	31	2	12	8	05.58	07.29	07.36	
69	22	14	56	5	3	6	06.03	07.32	07.48	

If observed further, it could be demonstrated that this is the only possible solution, i.e. that in fact there are three equal cases.

The duration of individual green light cycle will be determined on the basis of medium traffic intensity and the capacity of the queue, or on the basis of co-ordination between this crossroads and the other signalised crossroads. If, for example, vehicles from entrance **III** are considered, then red interval for the traffic directions 5 and 6 is not supposed to last longer than:

$$\mathbf{K}/\lambda$$

where **K** stands for capacity of the queue, and λ for the mean observed traffic intensity at this entrance.

For **K=30** and **λ=7.50** the calculation yields:

$$30 \text{ vehicles}/7.50 \text{ vehicles*min}^{-1} = 4 \text{ min}$$

while the same calculation for entrance II gives:

$$9 \text{ vehicles}/7.76 \text{ vehicles*min}^{-1} = 1 \text{ min and } 10 \text{ s.}$$

Consistently with the observed traffic intensity, the green phase for the directions 1 and 2 will last the longest.

For the sake of controlling the obtained result, i.e. the validity of the traffic light phase sequence at the crossroads, the new simulation was made with the following assumptions:

- green for the directions 1, 2 and 3 should last two minutes (one half of the maximal red interval for the directions 5 and 6),
- green for the other two signal groups should last one minute each,
- the simulation begins with the green phase of the signal group for the directions 1, 2 and 3,
- for better comparison, the same random numbers are used in this simulation as well in the previous one, which means that the sequence of arrivals at the entrances is equal to the preceding simulation, with one difference – here the direction is of significance,
- for determination of the traffic direction new random numbers were used in the scale from 1 to 10 (three individual sets) which are equally distributed for every traffic direction, so that, for example, at entrance I the numbers 1-5 determine the direction 1, and numbers 6-10 the direction 2.

The results are presented in Table 2.

For the observed case, immediately before the end of the 2nd minute, entrance II becomes saturated for the vehicles in the direction 4, which shows that the time chosen for the duration of the green phase has not been well determined. However, the saturation will occur even before, because of carriageway construction at traffic entrance II, where lane switching for direction 3 is not possible in case when four vehicles wait to pass in direction 4. In the given example, this would mean that congestion will occur 40 s after the beginning of the green phase, indicating that in case of a signal controlled crossroads that entrance would represent a serious problem. It is therefore ob-

Table 2

Number of arrival	Random numbers of decision			Order of service (Index by the entrance number means direction)	Number of vehicles in the queue		
	I	II	III		I	II	III
1	8	8	8	1st minute: I_2(0-2.5s) I_1(7-10.5s) I_2&II_3(12-14.5s) I_1(21-23.5s) I_1(24-26.5s) I_1(31-33.5s) I_1(33.5-36s) I_2(36-38.5s) I_1(38.5-41s)&II_3(37-39.5s) I_2(44-46.5s) I_1(51-53.5s) I_1(53.5-56s)	0	1	1
2	1	3	8		0	1	2
3	9	8	2		0	2	3
4	5	10	1		0	3	4
5	2	4	7		0	3	5
6	2	6	8		0	4	6
7	2	9	9		0	5	7
8	10	10	8	2nd minute: I_1(2-4.5s) I_2(10-12.5s)&II_3(11-13.5s) I_2(14-16.5s) II_3(17-19.5s) I_1(21-23.5s) I_1(30-32.5s) I_1&II_3(33-35.5s) I_1(35.5-38s) I_2(39-41.5s) II_3(45-47.5s) I_2(49-51.5s) I_1(58-60.5s)	0	6	8
9	5	1	3		0	6	9
10	8	3	5		0	6	10
11	3	8	4		0	7	11
12	3	3	7		0	7	12
13	5	4	2		0	7	13
14	7	8	1		0	8	14
15	8	7	6		0	9	15

vious that the time of the green phase interval must be carefully determined considering the arrivals of vehicles to the crossroads and the objective limitations which result from the very construction of the crossroads.

5. MANAGING OF SIGNALLING REGARDING PUBLIC TRANSPORTATION PRIORITY

The main reason for installing signalling at crossroads, that is, for traffic management by means of lights, is the safety of traffic participants. The throughput capacity is also included, which ensures the passing through of the non-priority traffic flows. The signalling management can be independent, fixed i.e. passive, or in the depending on traffic, that is on the given priorities. Since a substantial number of public transportation routes pass through this crossroads it is necessary to keep that fact in mind and adjust the signalling management to the priority of public transportation buses.

In order to achieve that priority it is necessary to announce the arrival of the bus on time, and this can be ensured by embedding the detectors in the form of inductive loops in the carriageway. To make sure that the signal is activated by a bus the detectors will consist of two inductive loops at a distance of 10 meters. Simultaneous occupation of both loops would be the sign of a bus arrival, but also of the arrival of trucks, tank trucks or similar long vehicles. To avoid the confusion, the detectors should be located in the carriageway at the previous bus stop, and the control signal should be generated at the moment the bus departs from the bus stop.

Then, depending on the signalling phase at the crossroads and the time needed for the bus to arrive to the crossroads, the adjustment of the signal begins. It is possible to achieve two levels of priority:

- passive priority, and
- active priority[2].

Passive priority means preventing the green phase for the conflicting signal group, while active priority is achieved by forcing the non-priority traffic directions to switch to red as soon as possible. Considering the concrete case and the distance of the bus stop to the crossroads, active priority would be more suitable here.

For the non-priority phases, this would mean the realisation of minimal green, and also, that the non-priority signal group may even be left out. In that care should be taken not to cause congestion again, due to signal managing depending on the priority, which can be resolved by placing the detector into the carriageway of the non-priority traffic direction and by

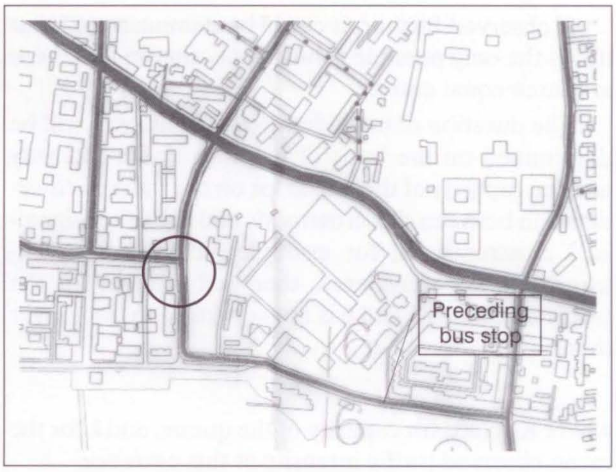


Figure 3

determining the number of vehicles above which the priority function would be cancelled. For maximum efficiency of management, it would be useful to place the detector also at the bus stop located immediately after the crossroads, thus achieving a double effect:

- the information that the announced bus has passed the crossroads would be received, and
- the arrival of the subsequent buses would be regulated, if these have been announced in the meantime, and taking into consideration the capacity of the bus stop.

6. CONCLUSION

Based on the mentioned observation for the concrete traffic problem, it is obvious that the urban traffic problematic is neither simple nor unambiguous. However, it is also obvious that often the only thing needed for better consideration of the same problem is just a little willingness. The considered problem requires first of all, more intensive co-operation between traffic and urban planning experts, because this is the only way of planning traffic capacities that will match the needs and will follow the development of the city. It is to be expected that this paper, even if it does not present the final solution, which was not its primary goal, will give incentive to a more responsible approach to the solution of this and similar problems.

SAŽETAK

SIMULACIJSKO MODELIRANJE ZAGUŠENJA PROMETA U KRIŽANJU

Zagušenje prometa pitanje je s kojim se u sve većoj mjeri suočava većina gradova. Posljedica je to neizbježne automobilizacije ali često puta i neprikladnih rješenje u izgradnji prometnica ili organizaciji prometa.

U članku se obrađuje jedno problematično križanje u gradu Zadru na kojemu, zbog loše organizacije dolazi do pot-

punog zastoja prometa. U prvom dijelu matematičkom simulacijom je pokazano je da će do zastoja sigurno doći, a u drugom dijelu se raspravlja o semaforizaciji križanja kao mogućem rješenju koje bi uz dodatak inteligentnog upravljanja signalnim fazama moglo znatno poboljšati organizaciju prometa kroz ovo križanje.

NOTES

1. www.random.org
2. M. Anžek, ... p. 51

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