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COMPARISON OF DELAYS AT SIGNAL-CONTROLLED INTERSECTION AND ROUNDABOUT

ABSTRACT

Delays belong to standard parameters used for the evaluation of any type of intersection and they are taken in the evaluation of the level of service of an intersection. Intersections with shorter delays bring about economical benefits both for the users and the community, and enable greater efficiency of a traffic system, which is becoming a significant criterion with the increasing motorization. The case studies carried out in Europe and worldwide reveal that roundabouts bring delay savings if compared with other intersections of the same operational level and nearly the same traffic volume. The paper shows the results of the comparison analysis of the roundabout and the signal-controlled intersection in the city of Osijek, Croatia. The statistical indicators have given the basis for the evaluation of delays at the observed intersections, offering at the same time the possibility to compare the analysis conclusions on the local level with the conclusions of the case studies carried out throughout Europe and worldwide.

KEYWORDS

delays, roundabout, signal-controlled intersection

1. INTRODUCTION

Three basic criteria are usually taken into account when evaluating the operational performance and efficiency of an intersection or a roundabout, and these are the capacity reserve (in some studies referred to as "the degree of saturation"), delays and queue lengths. Each of the mentioned criteria renders a unique perspective of geometric and operational characteristics of an intersection. Quantitative indicators presented numerically offer the possibility of comparing the operational performance and exploitation characteristics of different design alternatives, as well as different intersection types. Qualitative evaluation of the traffic flow is defined as the level of service (LOS), according to an adopted criterion.

Delays fall under standard parameters used for evaluating any intersection type (either signal-controlled or not) and they are added to the evaluation procedure of the level of service. Alternatives showing shorter delays at an intersection contribute to economies of the users as well as of the community and enable better efficiency of the system, which is becoming an important criterion with the increase of motorization.

A delay is the total time loss that vehicles are exposed to at an intersection, caused by the following:

- traffic conditions, weather conditions;
- geometric elements of an intersection, sight distance and traffic control;
- vehicle deceleration or acceleration;
- human behaviour [1], driver response time [2];
- influence of pedestrian [3, 4] and cyclist flow [6], crossing the arm of intersection [7].

A geometric delay, specific for roundabouts, is caused by the intersection geometry and not by the traffic conditions; Kimber [8] calls it a measurable geometric delay. A pure geometric delay is the time needed for a vehicle to pass through an intersection providing that a driver is sure that he will not be hampered by vehicles coming from the conflict traffic flow [8]. However, such delays cannot be measured under normal operating conditions.

The difference between total delays and geometric delays makes delays caused by the volume of a major traffic flow and traffic control and is called a "control delay" [9]. If total delays increase, the impact of geometric delays decreases (vehicles are at a standstill in a queue awaiting the gap availability in the major stream, or are stopped by the traffic control, in which case the intersection geometry has a slight impact on total delays). This leads to the conclusion that geometric delays are in the function of control delays. Control delays are the most frequently compared parameters in delays analyses.

Graph in [10] shows delays depending on the capacity reserve (1) for different levels of service.

$$R = Ce - Qe \tag{1}$$

R – capacity reserve (veh/h);

Ce – capacity of intersection (veh/h);

Qe – traffic volume (veh/h).

Professional literature presents some methods for evaluation of delays at roundabouts. Several formulae for estimating average delay at roundabout entries have been developed such as Kimber and Hollis [8], Highway Capacity Manual method [11], German method by Brilon [12], Australian method by Troutbeck [12].

Kimber and Hollis developed time-dependent delay solutions that consider oversaturated conditions. The basis of this method is probability distribution of different queue lengths as time functions, which are then used for determining the average queue length, as well as for computing the average queuing delay [12]. Field observations of the delays at roundabout entries indicate that the Kimber and Hollis method provides reasonable predictions fo under-saturated traffic conditions [8, 11].

Since the Kimber and Holis method is costly and time consuming, equations have been developed which give a good approximation to average queues calculated from a probabilistic theory. These were later simplified by Akçelik and Troutbeck and have been presented in the HighwayCapacity Manual. The simplified equations do not take into account time dependency or initial queues. The Highway Capacity Manual identifies a delay as the primary measure of effectiveness for both signalized and unsignalized intersections, with the level of service determined from the delay estimate [11].The data collected for roundabouts in the U.S. suggest that delays can be predicted in a manner similar to that used for stop-controlled and signal-controlled intersections. A modification is made to account for the yield control on the subject entry, which does not require drivers to come to a complete stop if there is no conflicting traffic [11].

Brilon designed a method for oversaturated unsignalized intersections based on reserve capacities. The complexity of many influencing parameters and the algebraic solutions make it impossible to solve the complete problem analytically. However, for two levels of approximation, a set of formulas is derived to estimate the average delay during a peak hour for the vehicles on the minor street of an unsignalized intersection.

Troutbeck equations for calculating delays were based on a gap acceptance theory. Limitation of calculated delays based on the traditional gap acceptance theory relied on the presumption that the major stream has absolute priority over the minor stream. Cowan [13] identified a number of different systems of merging operation where priority is shared between the two streams. Troutbeck realised [13] that the system of limited priority was most appropriate for a delays analysis. The probability of being delayed in a merging stream, due to waiting for an acceptable gap, is a valuable performance measure [13].

2. A SIGNAL-CONTROLLED INTERSECTION COMPARED TO A ROUNDABOUT IN TERMS OF DELAY CRITERION

2.1 State of the art

The comparison model of a signal-controlled intersection and a roundabout of a traffic artery of the same functional level [11] is based on a 24-hour evaluation under the same traffic volume conditions and taking into account the statistical distribution wit traffic volume factor being $D = 0.58$.

Annual delay savings have been evaluated on the basis of 250 working days per year (a conventional method that eliminates weekends and non-working days in a year). SIDRA[1] has developed an evaluation procedure, which can include or exclude annual delays caused by the geometric characteristics of an intersection. In this evaluation procedure the geometric delays have been included in the total annual delays at the intersection alternatives [11]. The evaluation results have been shown in the form of potential delay savings for a roundabout option in comparison to a signal-controlled intersection. Traffic volume and left turns percentages have been varied accordingly.

The roundabout brings out annual delay savings in all the observed conditions [11]; however, greater delay savings have been brought about with heavier traffic volume and higher left turn percentages. The observations illustrated on the example of the delay analyses overlap with a great number of case studies, as shown in the referenced literature [8, 12, 14], confirming the thesis that roundabouts do bring about delay savings, as opposed to the signal-controlled intersections.

The best operational characteristics of a roundabout are achieved at the saturation degree of up to 85%. At peak periods when the traffic volume of a roundabout approaches its full capacity, delays are more significant, catching up with the ones on a signal-controlled intersection, and under certain conditions the delays can be even longer. A signal timing design of a signalised intersection can be programmed for different conditions of traffic volume and can better accommodate traffic in the heaviest peak periods than non-signal intersections. It is for these reasons that each location should be analysed in the existing spatial and traffic conditions, since the principles of general applicability can yield rather poor results.

2.2 Experiment

Delays are usually analysed by evaluating the efficiency of an intersection reconstruction design, comparing delays before and after the reconstruction and, also, the two alternatives, as in this case is the comparison of a signal-controlled intersection and a roundabout. Since such analyses have not been carried out so far, it is only possible to compare different intersection types on the parallel and operationally similar traffic flows in the city of Osijek, Croatia (Fig. 1).

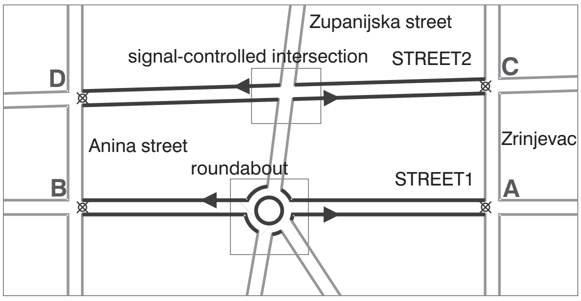

Figure 1 - Reference points for measuring travel time

Street1 and Street2 are two parallel city traffic arteries of primary importance and of identical operational levels. Between the observed points A and B in Street1 there is a roundabout, with a single-line approach in the double-line roundabout. Between the observed points C and D in Street2 there is the signal-controlled intersection. The signal control (traffic light control) operates in two temporally fixed programmes with the cycle length of 90 seconds. Both programmes (P1 and P2) have two phases and the first phase has two sub-phases. The green phase of the observed signal groups is shown in Table 1. Transition times of the observed signal groups in both directions are for the yellow light 3 seconds and for the red-yellow light 2 seconds.

Table 1 - Green phase

	P1 from 6 to 8.30 a.m. from 1.30 to 4.30 p.m.	P1 from 8.30 a.m. to 1.30 p.m. from 4.30 p.m to 10 p.m.
East - West	35 seconds	30 seconds
West - East	30 seconds	27 seconds

The measurements were made of the time it took a vehicle to pass through the roundabout between the reference points A and B and between the reference points C and D at the signal-controlled intersection (Fig. 1); the relevant data have been shown in the following tables. The measurements were made from February (icy roads) to May (dry pavement) at off-peak periods, in order to include the geometric delays in the total delays. The measurements were taken for 120 vehicles passing through each of the observed intersections in both directions.

The time measured in this way includes the travel time and delays at the intersection and it enables analysis of relative relations between the observed intersections.

Table 2 shows the traffic volume as counted at the observed intersections for a period of 15 minutes, three times during the day and once in the evening hours. The data were gathered using two video cameras which were videotaping the intersections for 15 minutes and the vehicle counting was done by looking at the recorded material. Detailed explanations and data can be found [14].

Table 2 - Traffic volumes at the observed intersections [14]

Time (h)	Traffic volume (veh/h)	
	Roundabout	Signal-controlled Intersection
8-9	2787	2043
11-12	3468	2022
15-16	3921	2625
20-21	3024	1749

The starting assumption is that data dispersion of the data from the mean value of the travel time between the reference points is smaller at the roundabout than at the signal-controlled intersection. Statistical indicators are to show whether the mean travel time through the roundabout is shorter or longer than the one through the signal-controlled intersection, since the traffic volume at the roundabout is heavier than the one at the signal-controlled intersection, which is shown in Table 2.

The travel time data are taken to be normally distributed. The measured travel time can be found [14]. Tables 3 to 7 show mean travel time values and statistical indicators.

Statistical indicators [15] are the following:

ti – measured travel time values (s);

N – total data $N = \sum_i fi$

fi – individual values frequency ti;

$\mu = \frac{1}{N}\sum_{i=1}^{N} fiti$ – arithmetic mean, mathematical expectation, central tendency measure;

ti_m – mean travel time of one group measured travel time values (s).

If there are no replications of the values, the frequency value is taken to be "1", out of which follows

$$\mu = \frac{1}{N}\sum_{i=1}^{N} ti;$$

$v = \frac{1}{N}\sum_i fi * (ti - \mu)^2$ – variation, mean square deviation from the arithmetic mean

$\sigma = \sqrt{v(t)}$ – standard deviation

Fcum – cumulative distribution function

Fver – probability density function

Kv – variation coefficient

A tabular presentation of the entire base of the measured data [14] would be too extensive, so that the measured travelling times were divided into 12 data groups. For each data group the mean travelling time value has been calculated and presented in a table, which has no impact on the value of the mathematical expectation, standard deviation or the variance. For the mean travel time values of each particular group of the measured data, cumula-

Table 3 - Mean travel time values and statistical indicators, Street1, East-West (roundabout)

Mean travel times / ti_m (s)											
79.6	71.6	71.2	70.4	68.6	65.8	65.2	63.8	62.2	59.8	57.8	49.2

ti_m (s)	80	72	71	70	69	66	65	64	62	60	58	49
Fcum	0.9665	0.7943	0.7565	0.7152	0.6708	0.5252	0.4748	0.4248	0.3292	0.2435	0.1717	0.0185
Fver	0.0094	0.0360	0.0396	0.0429	0.0457	0.0503	0.0503	0.0495	0.0457	0.0396	0.0322	0.0057
μ	65,5											
ti_m-μ	14.5	6.5	5.5	4.5	3.5	0.5	-0.5	-1.5	-3.5	-5.5	-7.5	-16.5
v	62.6363											
σ	7.9143											
Kv	12.0829											

Table 4 - Mean travel time values and statistical indicators, Street1, West-East (roundabout)

Mean travel times / ti_m (s)											
76.4	71.8	70.4	68.8	67.8	65.4	63.8	62.2	61.8	60.6	58.2	49.8

ti_m (s)	76	72	70	69	68	65	64	62	62	61	58	50
Fcum	0.9477	0.8523	0.7757	0.7302	0.6805	0.5144	0.4569	0.3457	0.3457	0.2942	0.1650	0.0166
Fver	0.0154	0.0333	0.0432	0.0477	0.0516	0.0575	0.0572	0.0532	0.0532	0.0497	0.0358	0.0060
μ	64.75											
ti_m-μ	11.25	7.25	5.25	4.25	3.25	0.25	-0.75	-2.75	-2.75	-3.75	-6.75	-14.75
v	48.0227											
σ	6.9298											
Kv	10.7025											

Table 5 - Mean travel time values and statistical indicators, Street2, East-West (signal-controlled intersect.)

Mean travel times / ti_m (s)											
94.8	90.2	88.4	84.6	80.2	76.8	76.2	70.2	66.8	65.8	41.8	40.4

ti_m (s)	95	90	88	85	80	77	76	70	67	66	42	40
Fcum	0.8959	0.8346	0.8046	0.7538	0.6556	0.5905	0.5681	0.4319	0.3657	0.3444	0.0381	0.0295
Fver	0.0103	0.0142	0.0158	0.0180	0.0211	0.0222	0.0225	0.0225	0.0215	0.0211	0.0047	0.0038
μ	73											
ti_m-μ	22	17	15	12	7	4	3	-3	-6	-7	-31	-33
v	305.4545											
σ	17.4773											
Kv	23.9415											

Table 6 - Mean travel time values and statistical indicators, Street2, West-East (signal-controlled intersect.)

Mean travel times / ti_m (s)											
89.6	89.2	86.4	83.6	82.2	75.4	70.7	64.6	61.8	59.8	59	49.8

ti_m (s)	90	89	86	84	82	75	70	65	62	60	59	50
Fcum	0.9003	0.8867	0.8382	0.7992	0.7551	0.5685	0.4216	0.2851	0.2148	0.1741	0.1557	0.0466
Fver	0.0130	0.0142	0.0181	0.0208	0.0233	0.0291	0.0290	0.0252	0.0216	0.0190	0.0177	0.0072
μ	72.6667											
ti_m-μ	17.33	16.33	13.33	11.33	9.33	2.33	-2.67	-7.67	-10.67	-12.67	-13.67	-22.67
v	182.4242											
σ	13.5065											
Kv	18.5869											

Table 7 - Statistical indicators of travelling time

	μ (s)	v	σ
EAST-WEST DIRECTION (A-B; C-D)			
Street1 (roundabout)	65.5000	62.6363	7.9143
Street2 (signal-controlled intersection)	73.0000	305.4545	17.4773
WEST – EAST DIRECTION (B-A; D-C)			
Street1 (roundabout)	64.7500	48.0227	6.9298
Street2 (signal-controlled intersection)	72.6667	182.4242	13.5065

tive function distribution values (Tables 3 to 6), as well as density distribution probability have been calculated (Tables 3 to 6 and Figures 7 and 8).

Table 7 shows synthesized statistical indicators.

Figures 2 and 3 show travel times for East-West and West-East directions both for the roundabout and the signal-controlled intersection (data histogram). Histograms show the groups of measured travel time data, as well as the mean values of the measured data of a particular group. As for the curves drawn through the mean values of the measured data groups, they adequately illustrate the measured data range, the distance of the particular data from the calculated total mean value, i.e., of the mathematical expectation both

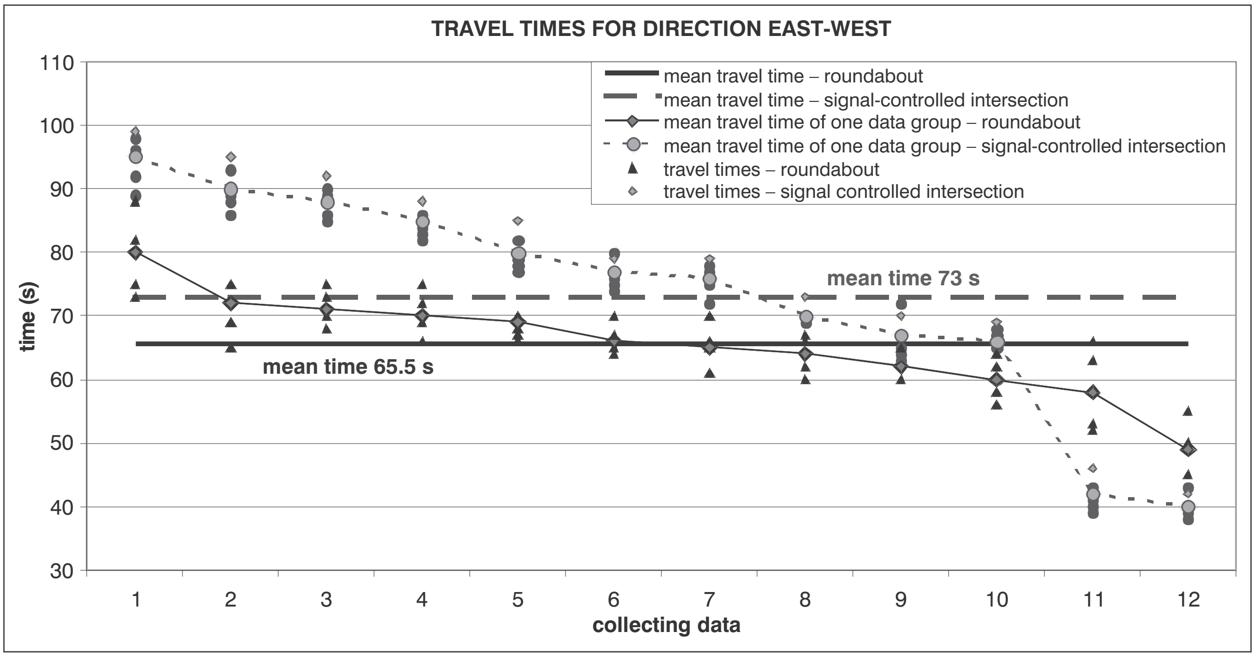

Figure 2 - Travel times for direction East-West, as measured

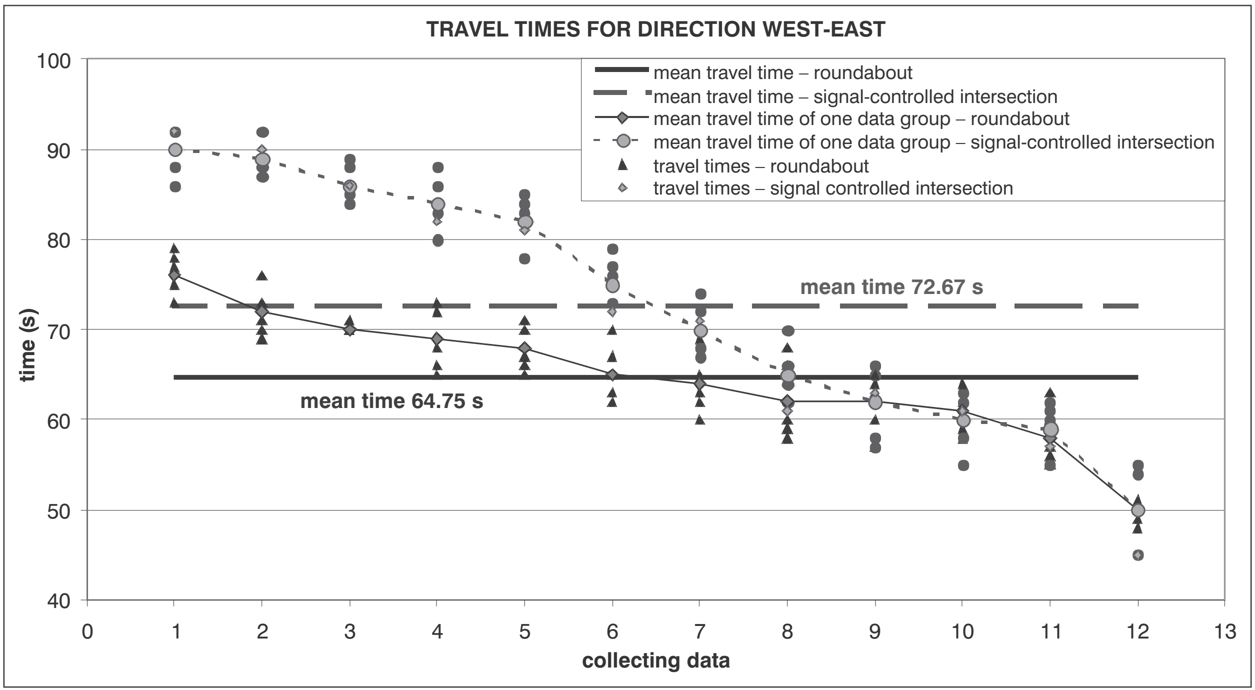

Figure 3 - Travel times for West-East direction, as measured

for the roundabout and for the signal-controlled intersection, for both driving directions.

Figures 4 and 5 show the probability density function, statistically illustrate the data distribution of travel times for the roundabout and the signal-controlled intersection [14] for both directions. The value of the density function of the mean values distribution of the measured data groups has been illustrated on the graph ordinate, while the abscissa illustrates the aberration value of a particular data of a data group mean value from the total measured data mean value. In such a way it is possible to present the function of the density distribution with different arithmetic means (μ) and different variances (σ^2) on the same graph.

3. DISCUSSION

For the distribution of the measured travel time data, a model of normal data distribution has been assumed. The assumption that the measured datum will be normally distributed will be checked by the probability that the data is likely to be found within a certain range, namely for [16]:

1. (μ-σ) and (μ+σ) representing 68.45%;
2. (μ-2σ) and (μ+2σ) representing 95.45%;
3. (μ-3σ) and (μ+3σ) representing 99.73%

of the normally distributed independent variables.

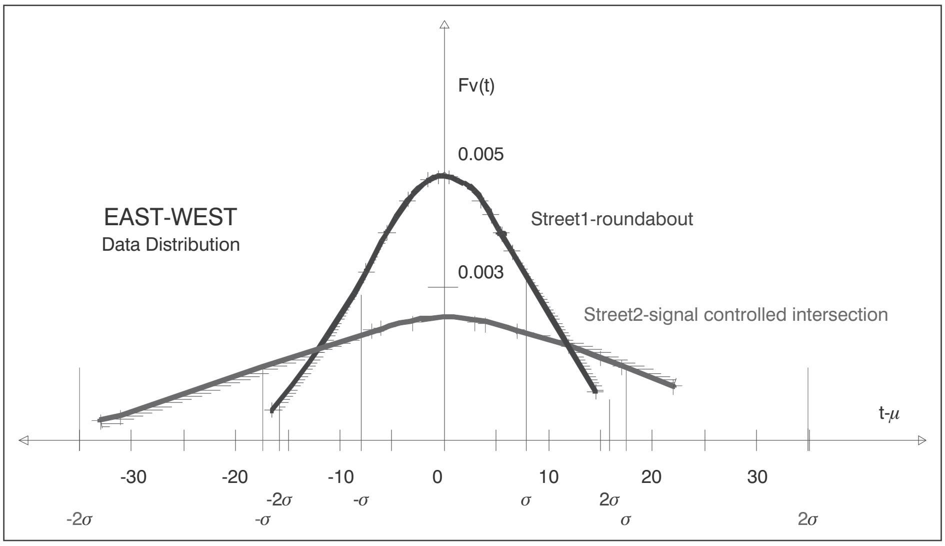

Figure 4 - Data distribution of travel times for the roundabout and the signal-controlled intersection, East-West direction

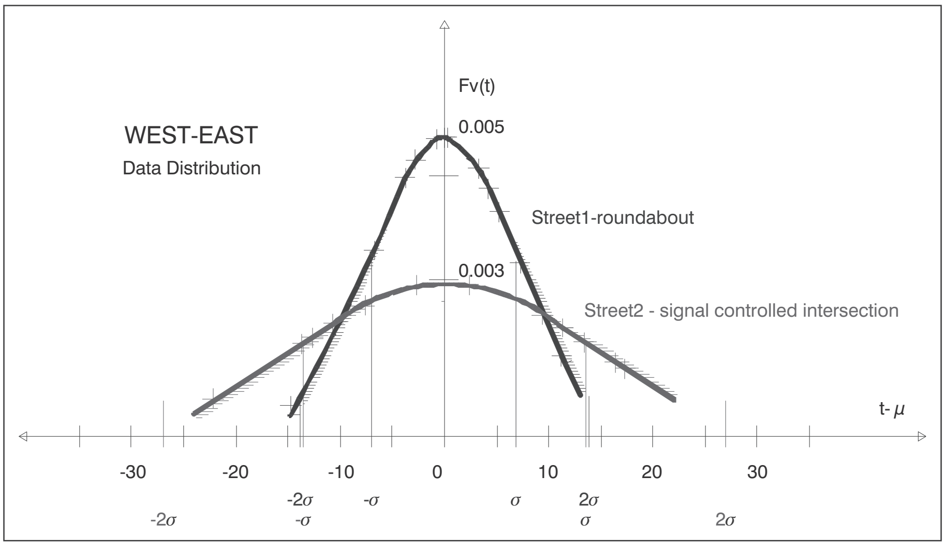

Figure 5 - Data distribution of travel times for the roundabout and the signal-controlled intersection, West-East direction

The first condition $\mu \pm \sigma$ for the roundabout satisfies the following:

- 83% of data groups mean values, i.e. 78% of the total database for East-West direction,
- 75% of data groups mean values, i.e. 72% of the total database for West-East direction.

The signal-controlled intersection satisfies the following:

- 75% of data groups mean values, i.e. 70% of the total database for East-West direction,
- 75% of data groups mean values, i.e. 69% of the total database for West-East direction.

The first condition for the normally distributed independent variables has been satisfied for all the measured data.

The second condition $\mu \pm 2\sigma$ for the roundabout satisfies the following:

- 92% of data groups mean values, i.e. 94% of the total database for East-West direction,
- 92% of data groups mean values, i.e. 95% of the total database for West-East direction.

The signal-controlled intersection satisfies the following:

- 100% of data groups mean values, i.e. 100% of the total database for East-West direction,
- 100% of data groups mean values, i.e. 97% of the total database for West-East direction.

The second condition for the mean values of data groups in the roundabout seems not to be satisfied (one datum for both directions falls out from the given range). However, the database of the total measurements shows better statistical access. Also, 94% of data (East-West) and 95% of data (West-East) are found within the given range, that is to say that the total measured database satisfies the given condition. The falling out of an insignificant number of data from the given range can be explained by the fact that only rarely a vehicle has not been disturbed either by the conflict traffic flow or by the pedestrian or cycling flow, which have the right of way at the roundabout. Such a number of data is statistically insignificant and has no impact on the variance.

As for the third condition $\mu \pm 3\sigma$, it was entirely satisfied, 100% of all data is found within the given range, for both intersections and both directions.

Checking of the standard deviation value for the normal distribution according to the criterion [16]:

$$2 < \text{measured data range}/\sigma < 6.5 \qquad (2)$$

has been made and satisfied for all the measured data.

The presented analysis indicates a satisfactory grouping of data around the mean values of the measured travelling times and it also adequately overlaps with the assumed normal distribution. The comparison of the roundabout and signal-controlled intersection according to the statistical parameters of the normal distribution ensures a valid estimation of the research subject.

The graphs in Figures 4 and 5 illustrate that the function of the distribution density for the signal-controlled intersection for both directions is wider and lower, which indicates higher variance value, i.e. greater dissipation of data around the mean value.

Mean travel time through a signal-controlled intersection is longer than that through the roundabout, while the statistical parameters confirm the assumption that the dispersion of data from the mean value of the travelling time between the reference points is smaller at the roundabout than that at the signal-controlled intersection (Tables 3 to 6).

4. CONCLUSION

The conclusions of the analyses of the roundabouts resulting from a number of case studies throughout Europe and worldwide indicate that at intersections of the same operational level and of nearly the same traffic volume, roundabouts offer delay savings, if compared with any other alternative. Time saving depends on the traffic volume and left turns percentages at an intersection. Higher percentages of left turns reduce the operability of any type of intersection, with relatively insignificant effect on a roundabout.

The measurements taken for the travelling time between the reference points at the observed roundabout and the signal-controlled intersection in the city of Osijek have revealed the following:

- delay savings of roundabout versus signal-controlled intersection are notable;
- according to the statistical parameters, the dispersion of data from the mean value of the travelling time between the reference points is smaller at a roundabout.

The conclusions arising from the analysis of the delays at roundabout and signal-controlled intersection in the city of Osijek indicate good overlapping with the conclusions of the case studies carried out throughout Europe and worldwide.

The greatest delay savings are brought about at roundabouts during off-peak periods, that is to say, when they operate with at least 15% of capacity reserve.

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SAŽETAK

USPOREDBA VREMENSKIH GUBITAKA NA SEMAFORIZIRANOM I KRUŽNOM RASKRIŽJU

Vremenski gubitci spadaju u standardni parametar koji se koristi za ocjenu bilo kojeg tipa raskrižja i ulaze u ocjenu razine usluge raskrižja. Raskrižja koja daju manje gubitke vremena predstavljaju ekonomsku dobit za korisnike i zajednicu i omogućuju veću djelotvornost mreže, što s rastom motorizacije postaje važan kriterij. Prometne studije rađene u Europi i svijetu pokazuju da kružna raskrižja imaju manje vremenske gubitke u usporedbi s drugim površinskim raskrižjima iste funkcionalne razine i približnog prometnog opterećenja. U radu su prikazani rezultati analize usporedbe kružnog raskrižja i semaforiziranog raskrižja u gradu Osijeku, Hrvatska. Statistički pokazatelji dali su temelj za ocjenu vremenskih gubitaka u promatranim raskrižjima, a ujedno i mogućnost usporedbe zaključaka analize u lokalnim uvjetima sa zaključcima prometnih studija rađenih u Europi i svijetu po kriteriju vremenskih gubitaka.

KLJUČNE RIJEČI

vremenski gubitci, kružno raskrižje, semaforizirano raskrižje

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