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AN ANALYSIS OF INTERSECTION TRAFFIC SIGNAL WARRANTS

ABSTRACT

This paper presents an analysis of the existing traffic signal warrants and the corresponding threshold values. The analysis of unsignalized intersections was conducted according to the analytical procedures of Highway capacity manual. Traffic signal optimization was conducted using Synchro software. The results showed that the current warrants are not sufficiently reliable in some situations and can be misleading in the process of selecting the intersection control type. There are three major reasons for insufficient reliability of the existing warrants. First, they are primarily based on total major and subject minor street volumes, so they do not take into account all the possible combinations of volume distribution and composition of the turning maneuvers. Second, they do not make difference between three-leg T intersections and four-leg intersections, and finally they are based only on an overall system operation without regarding the functionality of a specific approach.

KEYWORDS

traffic signal warrants; intersection delay; traffic volume distribution, four-leg intersections, T intersections

1. INTRODUCTION

There are a limited number of resources for determining the optimum intersection traffic control type. The practitioners typically rely on the MUTCD (Manual of Uniform Traffic Control Devices) [1] warrants or in some cases on the ITE (Traffic Engineering Handbook) [2] and the guidelines provided in the HCM methodology [3].

MUTCD provides a detailed set of 11 warrants each of which justifies the imposition of traffic signals at an intersection. This paper deals with four of these warrants that are directly related to traffic volumes. Other warrants are connected with pedestrian volume, accident experience, progressive movements and the role in road network.

The first two warrants, i. e. Warrant 1, Condition A - *Minimum vehicular volume* and Warrant 1, Condition B - *Interruption of traffic flow* are the oldest and they apply to an 8-hour qualifying period. Warrants 3 and 4, namely *Peak ho*ur and *Four-hour vehicular volume* warrants were added in 1985 when a new version of HCM was introduced. These warrants and their threshold values were established many years ago. They are based largely on the engineering judgment and reflect the sensitivity to two variables only; approach volumes and number of lanes. Their subjective basis and limited sensitivity make them inaccurate predictors of the need for signal control at some intersections.

In fact, several separate evaluations of the MUTCD warrants found that in many situations they do not always yield conclusions that agree with the conducted engineering studies.

Thus, for example, Williams and Ardekani [4] have conducted field and simulation studies of a number of intersections which were identified as marginally warranted. The simulation results showed that, in all cases studied, the actuated traffic signals yielded significantly greater delays than two-way stops.

Saka [4] used the microscopic simulation model to estimate the minimum threshold that requires the installation of traffic signals at intersections. The result obtained from the simulation experiment indicates that MUTCD warrants are conservative for some situations and hence, if rigidly applied, can result in premature installation of traffic signals. Also, the simulation experiment confirmed that there is a need for different threshold values for three and four-leg intersections.

Consequently, many experts believe that these warrants are not so practical and efficient. There is an ongoing discussion concerning further revisions of these warrants, including the deletion of warrants 1, Condition A and Condition B.

Wainwright [6] gave maybe the best review of the status of signal warrants at the time of the introduction of Warrants 3 and 4 noting that:

a) the volumes in Warrant 1, Condition A and Condition B, have little quantitative basis, originating in 1920s and 1930s as the consensus of experts serving on the AASHO committee at the time;

b) the 8-hour requirement was also the expert consensus of these experts, being a period on which they could agree;

c) Warrants 1 and 2 are based on the minimum threshold value rather than on a sliding scale or combined volume, so that intersections with a major street below the threshold and minor street very close to the same level might have more total conflicting volume (and not trigger the warrant) than an intersection that just meets each threshold.

For these reasons a few authors proposed new warrants. Neudorff [7] proposed gap-based criteria for signal warrants. Brettherton [8] proposed two A. M. and two P. M. peak hour conflicting traffic turning movements as criteria for traffic signal warrant. Sampson [9] suggests a warrant based on an average queue length (which itself includes two variables, namely delay and volume) of vehicles, pedestrians or cyclists, measured at regular intervals and averaged over the peak hour. Still, none of these warrants has been accepted.

Marek et al. [10] suggest a guide for selecting the intersection traffic control based on peak hour intersection volumes and the resulting delay, *v/c* and average queue length. The three graphs result from the appliance of the HCM 1997 methodology for the analyzed generic intersection and the assumed unique volume split. In this guideline the criterion for optimum traffic control is based on the average delay (or queue length) of all vehicles entering the intersection. HCM guideline shown in exhibit 10-15 is based on the same principle. This can often lead to situations where the average overall delay on unsignalized intersection is less than on the signalized one, but the subject minor street vehicles suffer unacceptable delay (or queue length and other measure of effectiveness).

2. OBJECTIVE

It can be noted that the existing warrants and guidelines do not take into account the volume split on the major street and traffic volume distribution between approaches as well as the proportions of specific maneuvers on minor and major approaches. The most conflicting maneuver on a signalized as well as on an unsignalized intersection is the left turning maneuver and its proportion should have the most negative impact on the intersection operation and the resulting measures of effectiveness. Consequently, it can be concluded that the existing and recently proposed traffic control warrants and guidelines are not based on a real measure of effectiveness (MOE) of an intersection.

Besides, neither warrant gives specific different values for T intersections and four-leg intersections, although it is clear that there are more conflicting maneuvers on a four-leg intersection. This can result in a less efficient functionality and significantly greater delays on the four-leg intersection than on the T intersection for the same traffic volumes distribution on a major and a higher volume minor street.

Therefore, this research was initiated with the objective to conduct a detailed analysis of current threshold values of the existing warrants, then to comprehend their reliability and the traffic variables which exert a significant impact on the quality of traffic operations on an isolated intersection.

3. ANALYSIS OF EXISTING TRAFFIC SIGNAL WARRANTS

In this paper a detailed analysis of unsignalized and signalized three-leg and four-leg intersection operations for MUTCD traffic volume threshold values was conducted using Synchro software. In order to compare the functionality of unsignalized and signalized intersections some "generic" traffic and geometry characteristics of intersections were developed. Throughout this analysis, it was assumed that the intersection is isolated from the impact of any adjacent intersection. Other important assumptions include that all traffic is uniform and composed of passenger car units, with a gradient of 0%, there are no parking maneuvers and the peak hour factor is 0.9.

The analyzed intersection geometric cases are shown in Figure 1.

Different volume split combinations were analyzed i. e. a 50/50 split per direction was assumed in major street, while the traffic on the minor street was split 70/30 for the higher volume and opposing direction of minor street.

On T intersections the proportions of 10 and 30 percent of left turning vehicles were assumed, while on four-leg intersections the proportions of 10 and 20% of left and right turning maneuvers were assumed in each major street direction.

The proportions of 10 and 50 percent of left turners in the higher volume minor street on T intersections were analyzed for all other combinations of volume splits and intersection geometries. Table 1 shows the analyzed range of traffic volume distribution, i. e. minimum and maximum assumed percentages of turning maneuvers for all the analyzed geometric cases of three- and four-leg intersections.

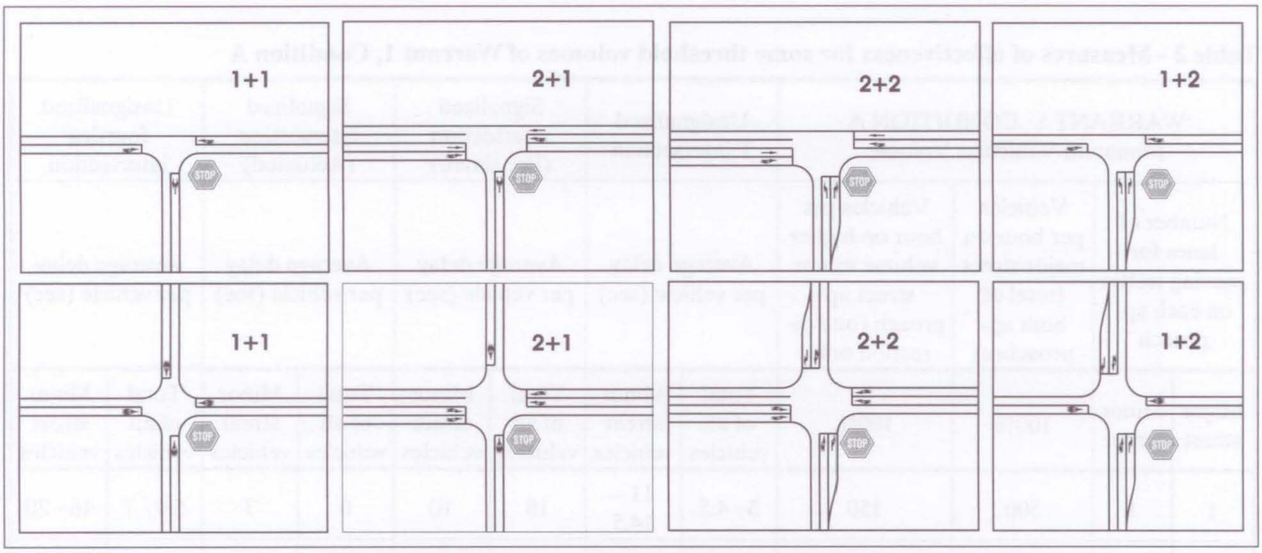

Figure 1 - Analyzed hypothetical intersection configurations

Table 1 - Analyzed combinations of traffic volume distribution

Direction	No. of Legs	Total Split	Left Split		Through Split		Right Split	
			Major Leg					
Major 1	3	50%	10%	30%	90%	70%	–	–
	4	50%	10%	20%	80%	60%	10%	20%
Major 2	3	50%	–	–	80%	90%	20%	10%
	4	50%	10%	20%	80%	60%	10%	20%
			Minor Leg					
Minor 1 (Higher Volume)	3	100%	10%	50%	–	–	90%	50%
	4	70%	20%	25%	60%	50%	20%	25%
Minor 2	3	0	–	–	–	–	–	–
	4	30%	20%	25%	60%	50%	20%	25%

Numerous calculations were conducted according to the analytical procedures for signalized and unsignalized intersections. Traffic signal optimization analyses were conducted using the Synchro software. The criterion for choosing optimal traffic signal scheme was based on the average overall delay. The traffic signal data used in calculations assume the cycle length of minimum 55 seconds and lost time per phase of 4 seconds.

Tables 2-5 show the resulting measures of effectiveness for some selected threshold volumes of Warrant 1, Condition A, Condition B, Warrant 2 and Warrant 3, Condition B. The results are shown for unsignalized three-leg and four-leg intersections and for the signalized intersections (pre-timed and actuated). In the case of unsignalized intersections the range of results is shown according to the volume distribution and the corresponding proportion of left turning vehicles in major and minor streets.

For the case of signalized intersections there were no significant differences in the resulting measures of effectiveness for three-leg and four-leg intersections nor for different proportions of left-turning vehicles. Therefore, Tables 2-5 show the average values.

The resulting measures of effectiveness show that unsignalized T intersections operate with less average overall delay than the corresponding signalized intersections (pre-timed as well as actuated) for all threshold volumes of Warrant 1, Condition A and B. Also, all the minor approach average delays are acceptable (the greatest delay corresponds to the boundary between level of service (LOS) C and LOS D according to the HCM methodology. On four-leg intersections even the worst possible traffic volume distribution results in significantly better operation of actuated signalized intersection over unsignalized one. Pre-timed signals do not result in less overall average delay for none of the analyzed combination of traffic volume distribution. So, one can note that the first two warrants, i. e. Warrant 1, Condition A and Condition B are not reliable guides in the selection process of optimal intersection control type. This is the consequence

Table 2 - Measures of effectiveness for some threshold volumes of Warrant 1, Condition A

WARRANT 1 CONDITION A Minimum Vehicular Volume				Unsignalized T intersection		Signalized intersection (Pre-timed)		Signalized intersection (Actuated)		Unsignalized four-leg intersection	
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)	Vehicles per hour on higher volume minor street approach (one direction only)	Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)	
Major street	Minor street	100%	100%	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles
1	1	500	150	3– 4.5	11 – 14.5	10	10	6	7	5.4 - 7	16 - 20
2	1	600	150	2.5-4	11 - 15	9	8	5	6	5 -7	18 - 23
2	2	600	200	3 – 4.5	13 - 19	9	8	5	6	6 -9	23 - 32

Table 3 - Measures of effectiveness for threshold volumes of Warrant 1, Condition B

WARRANT 1 CONDITION B Interruption of Continuous Traffic				Unsignalized T intersection		Signalized intersection (Pre-timed)		Signalized intersection (Actuated)		Four-leg unsignalized intersection	
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)	Vehicles per hour on higher volume minor street approach (one direction only)	Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)	
Major street	Minor street	100%	100%	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles
1	1	750	75	2-3	12-18	9	10	4	9.5	3.3-5	19 - 25
2	1	900	75	1.3- 3	11-19	9.5	8.5	3.5	7	3-5	22 - 32
2	2	900	100	2-3	17-27	9.5	8	4	7	4-6	31-45

of establishing these warrants as a consensus of experts.

Furthermore, from the current practice of road design, these warrants are practically useless since at many locations the A. M. and P. M. peak hours experiencing the most intense traffic determine the geometric design and traffic control of an intersection regardless of the traffic volumes for the rest of the day.

The presented results show great differences between the MOE of three and four-leg unsignalized intersections. Thus, the average delays of all vehicles for a three-leg unsignalized intersection with two lanes in major and one lane in minor street, for the threshold volumes of Warrant 2, vary from 3 to 10 seconds, and the average delays for minor street vehicles vary from 13 to 32 seconds, according to the conflicting traffic volumes and the proportion of left turners in major and minor streets. For the same volumes the average delays on a four-leg intersection varied from 8 to 26 seconds, while the average delays of minor street vehicles varied from 31 to more than 100 seconds, which is not acceptable. For other geometric cases the results are more significant. Threshold traffic volumes of a *peak hour warrant*, Condition B, result in unacceptable delay on a subject minor street (more than 100 seconds) for all analyzed geometric cases of four-leg intersections and for all combinations of volume distribution.

The analysis of intersection operation at threshold traffic volumes of criteria 2 and 3 shows a significant difference in operation of three and four-leg intersections for the same traffic volume distribution on major and subject minor street. Also, in many situations, wrong conclusion about not installing the signal control at places where they are obviously needed would be accepted according to the existing warrants, especially for four-leg intersections. This misleading possi-

Table 4 - Measures of effectiveness for threshold volumes of Warrant 2

WARRANT 2 Four-Hour Traffic Volume				Unsignalized T intersection		Signalized intersection (Pre-timed)		Signalized intersection (Actuated)		Four-leg unsignalized intersection	
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)	Vehicles per hour on higher volume minor street approach (one direction only)	Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)	
Major street	Minor street	total of both approaches	(one direction only)	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles
1	1	600	220	4-7	13.5 - 21	10	10	7	8	9 –13.5	26 -40
		800	150	3 – 5.5	14 – 25.5	9	12	6.5	10	7-11	31-52
		1000	95	2 –4.5	15 - 31	8	13	5	12	5-9	35-64
		1200	80	2 – 5.5	17 - 49	7 - 12	14 - 18	4-7	13-20	6-12	54->100
2	1	400	390	6.5 - 10	13-19.5	9.5	7.5	7	5.5	16-26	31-55
		600	285	4.5- 8	12.5-22	10	8.5	7	6	12-23	33-66
		800	205	3 – 6.5	13-26	10	9	6	7	10-21	37-86
		1000	145	2 –5.5	13-32	9	10	5	7.5	8-18	44->100
2	2	600	385	5 - 8	14-26	9	8.5	4-7	6.5	16-48	55->100
		800	280	3.5-7	16-37	10	8	6.5	6	14-44	68->100
		1000	195	2.5-6.5	20-52	9	9.5	5.5	8	11-36	81->100
		1200	135	2 - 6	25-73	9	10	5	9	9-30	>100

bility is, among other things, a consequence of choosing the average delay of all vehicles entering an intersection as a criterion for optimal intersection control type. The resulting measures of effectiveness show that there are many situations when the overall average delay on an unsignalized intersection is less than on the signalized one, but the subject minor street vehicles suffer unacceptable delay (over 100 seconds). The other factor that contributes to the unreliability of the existing warrants is that they do not take into account the volume distribution and the proportion of left turning vehicles in major and minor streets.

The situation with other peak hour guidelines for optimal intersection control type is pretty similar. Thus, for example, the HCM guide for intersection control type (as shown in exhibit 10-15 of HCM 2000) and guidelines shown in paper [10] by Marek et al. are similar to MUTCD peak hour warrant, Condition B, resulting in similar consequences.

This research also showed that according to Warrant 1, Condition A and Condition B, one should conduct a detailed engineering study about installing signal controls in many situations in which all the measures of effectiveness demonstrate satisfying or even better functionality of an unsignalized intersection over a signalized one.

This research also included numerous calculations for different combinations of the volume split and composition of turning maneuvers in order to comprehend the traffic variables which exert a significant impact on the quality of traffic operations on an isolated intersection. With the selected volume distribution, the major street volume ranged from 400 to 1,600 vehicles per hour (veh. /h). Volume tables were developed with increments of 100 veh. /h for major street approaches resulting in sets of data of more than 200 potential volume combinations for each of the analysed intersection geometric case. Figure 2 presents some of the results for unsignalized T intersection with one lane in major and one lane in minor street. In the presented Figure there are two sets with three lanes for each major street total volume. The difference between sets is in the proportion of left turning maneuvers, i. e. 10% or 30% of left turning vehicles in major street. Three lanes per set correspond to the proportion of left turning vehicles in minor street (10%, 30% or 50%). Only a part of the analyzed volume combinations data are presented here.

This study indicated that the proportions of left turn maneuvers in major and minor streets, in addition to the total volume in the major street, exert the most significant impact on the quality of the intersec-

Table 5 - Measures of effectiveness for threshold volumes of Warrant 3, Condition B

WARRANT 3 Peak Hour				Unsignalized T intersection		Signalized intersection (Pre-timed)		Signalized intersection (Actuated)		Four-leg unsignalized intersection	
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)	Vehicles per hour on higher volume minor street approach (one direction only)	Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)		Average delay per vehicle (sec)	
Major street	Minor street	100%	100%	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles	Total of all vehicles	Minor street vehicles
1	1	600	370	7.5-19.5	19 - 49	11	9	9	8	38-77	>100
		800	280	5.5-19	20 - 66	10	12	8.5	10	33-77	>100
		1000	200	4-16	20 - 82	9	14	8	11.5	25-65	>100
		1200	145	3-15	21->100	8 - 13	15-20	6-11	13-20	20-60	>100
2	1	800	370	6-30	17 - 90	11	8	8	7	70->100	>100
		1000	285	4 - 27	17->100	10.5	9.5	7.5	8.5	60->100	>100
		1200	220	3 - 27	17->100	10	11	7	9.5	57->100	>100
2	2	1000	377	4.5 - 26	21->100	10	9.5	7.5	8.5	>100	>100
		1200	285	3.5 - 26	26->100	9	11	7	9.5	>100	>100

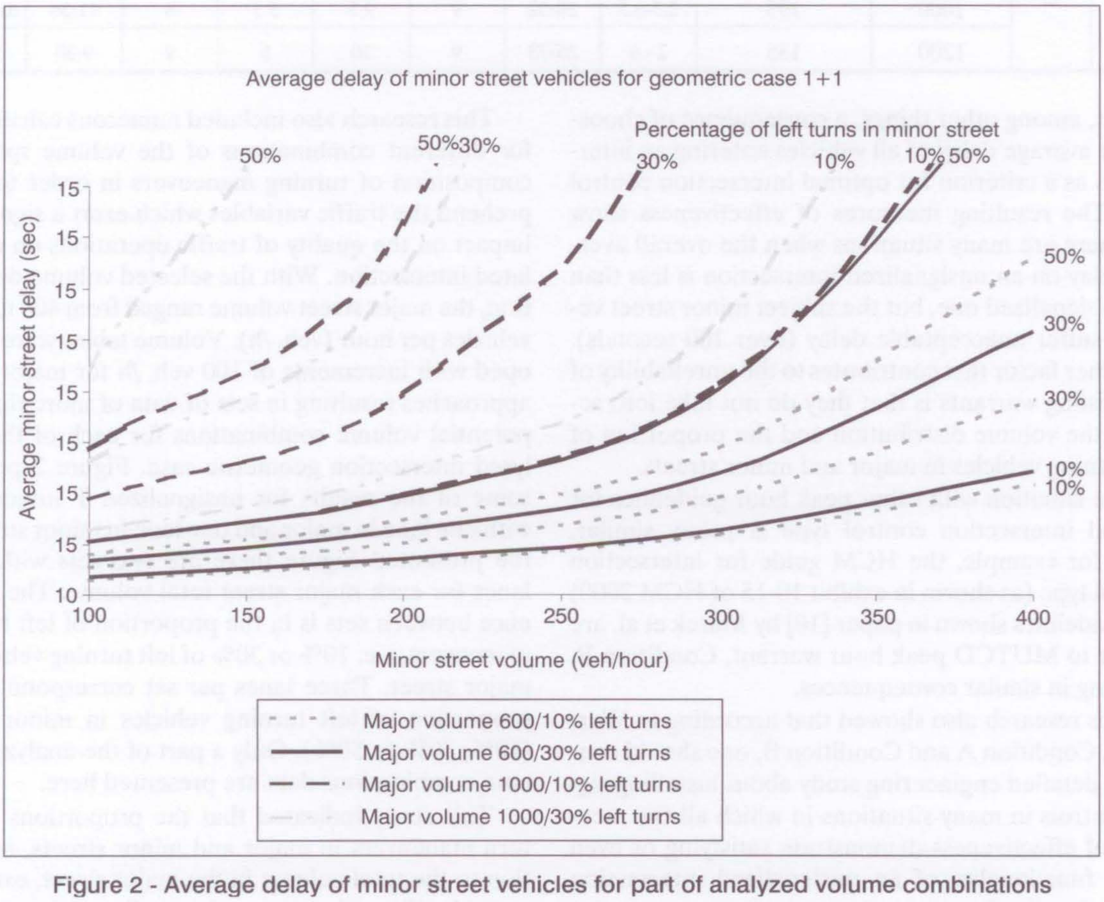

Figure 2 - Average delay of minor street vehicles for part of analyzed volume combinations

tion traffic for all the geometric cases and traffic control types. The volume split per major street direction exerts less influence on the traffic operation.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Delay is one of the major measures of intersection effectiveness. There are several factors that affect vehicle delay at intersection, such as the traffic volume distribution and the composition of turning manoeuvres. However, none of the existing warrants has ever covered this issue directly. Since volume data are commonly measured it has become a surrogate for other measures of effectiveness. Therefore, the existing warrants are not reliable guidelines in the selection process of the intersection control type.

This study shows that there are three major reasons of insufficient reliability of existing warrants. First, they are primarily based on total major and minor street volumes, so they do not take into account different combinations of volume distribution. Second, they do not give separate threshold values for three-leg intersections and finally, some of them, i. e. Warrant 2 and Warrant 3 are based only on overall system operation, i. e. average delay of all vehicles entering the intersection, regardless of the quality of traffic operations of a specific approach. The resulting measures of effectiveness show that there are many situations when the overall average delay on an unsignalized intersection is less than on the signalized one, but the subject minor street vehicles suffer unacceptable delays (over 100 seconds).

Based on the results of this research the authors suggest possible improvements of traffic signal warrants:

- the future warrants should include a criterion based on combination of local and system measure of effectiveness;
- they should include the impact of traffic volume distribution and composition of turning maneuvers;
- there is a need for separate threshold values for T intersections.

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SAŽETAK

U radu su analizirani postojeći kriteriji za izbor tipa kontrole raskrižja kao i njihove granične vrijednosti. Provedeni su brojni proračuni po analitičkim procedurama metodologije Highhway capacity manual, a optimizacija rada semafora i rezultirajuće mjere efikasnosti raskrižja dobivene su primjenom programa Synchro. Dobiveni rezultati ukazuju na nepouzdanost postojećih kriterija u mnogim realnim situacijama što može rezultirati donošenjem pogrešnih odluka o izboru optimalnog tipa kontrole raskrižja. Postoje tri najvažnija uzroka nepouzdanosti postojećih kriterija. Prvi je taj što se oni temelje samo na ukupnoj veličini prometa na glavnim i sporednim privozima, odnosno ne uzimaju u obzir raspodjelu prometa po privozima te učešće pojedinih manevara kretanja. Drugi razlog je taj što postojeći kriteriji ne postavljaju posebne vrijednosti za trokraka raskrižja. Posljednji je razlog to što se neki od kriterija temelje isključivo na funkcionalnosti raskrižja u cijelini ne uzimajuci u obzir funkcioniranje pojedinih privoza raskrižja.

KLJUČNE RIJEČI

prometna signalizacija, efikasnost raskrižja, kontrola raskrižja, raskrižja

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