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GAP ACCEPTANCE AT NON–STANDARD UNSIGNALISED INTERSECTIONS

ABSTRACT

Non-standard unsignalised intersections are very common in European countries with old street networks. The major road often bends at an angle at the centre of an intersection, which makes the intersection non-standard. There are very few papers about the capacity analysis and headway values at these intersections, even though non-standard intersections are widespread not only in Europe but also in the rest of the world. Regarding the fact that priority at the non-standard unsignalised intersection (NSUI) differs from the standard unsignalised intersection (SUI) and the conflict flows, it can be expected that headways are not the same as those at the SUI. Consequently, the capacity at the NSUI differs from that at the SUI. This paper gives critical headway and follow-up headway values at 3-leg and 4-leg NSUI collected by on-field measurement. Recommendations for the values used for the capacity analysis are given, and recommended values are compared at SUI and NSUI.

KEYWORDS

capacity; priority; non-standard unsignalised intersection; gap acceptance; follow-up headway; critical headway.

1. INTRODUCTION

Unsignalised intersections with STOP or YIELD signs placed at minor approaches are called two-way stop-controlled intersections (or TWSC). These intersections are most common at street and road networks.

Non-standard unsignalised intersections (NSUIs) are intersections where the major road bends at the centre of the intersection. These intersections are often standard in geometry (3 legs or 4 legs), but non-standard when it comes to the way of traffic regulation. If the major road is a part of a vital state road, it must have priority, even if it bends to the left or right in the middle of the intersection. For that reason, making intersections non-standard is the only possible way of traffic regulation. Most NSUIs are in the European cities with old road networks.

NSUIs are a special type of two-way stop-controlled intersections (TWSC), where major and minor approaches are not the same as at SUIs. For that reason, there are different traffic conditions at NSUIs and standard procedures for capacity analysis that cannot be used. Major and minor approaches layout at an NSUI is significantly different from a standard TWSC intersection with the same geometry. The major road at an NSUI bends, which makes the major and minor movements at these intersections unique, with very specific conflict flows [1].

Regarding the fact that NSUI is a special type of TWSC, the basic principle for the capacity analysis [2] can be applied for capacity calculation, as well as a formula that is given in HCM 2000 [3] HCM 2010 [4] and HCM 2016 [5].

On the other hand, since the conflict flows and other traffic parameters (visibility, vehicle speeds) are different at the NSUI than at the SUI, it can be assumed that critical headways and follow-up headways are different. According to the preliminary research at the 3-leg NSUIs [6], it has been proved that critical headways and follow-up headways are different from the standard unsignalised 3-leg intersections.

This paper gives the values of critical headways and follow-up headways at 3-leg and 4-leg NSUI for the first time because these values were not determined before. Values were measured in different cities/states and traffic conditions. According to on-field measurements, the recommended values of headways at NSUIs are given.

2. WHAT IS AN NSUI?

A non-standard TWSC intersection is an intersection where the major road bends at the centre of an intersection. These intersections generally have a standard geometry (3-leg or 4-leg). At the same time, their non-standardised layout, which is reflected in the way of traffic regulation, means the positions of major and minor approaches differ from those at standard unsignalised intersections. At standard intersections, the major and minor approaches are opposite, while at the non-standard ones, they are side by side.

The position of approaches and the difference between standard and non-standard TWSC intersections are given in the following figures. *Figure 1* shows a typical 4-leg standard, and *Figure 2* shows a typical 4-leg non-standard TWSC intersection.

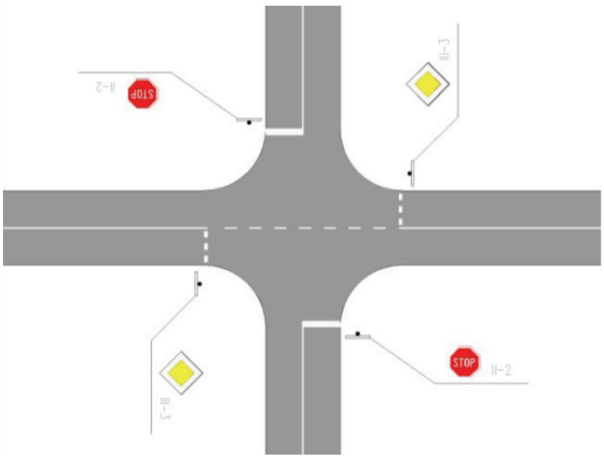


Figure 1 – Typical 4-leg standard TWSC intersection

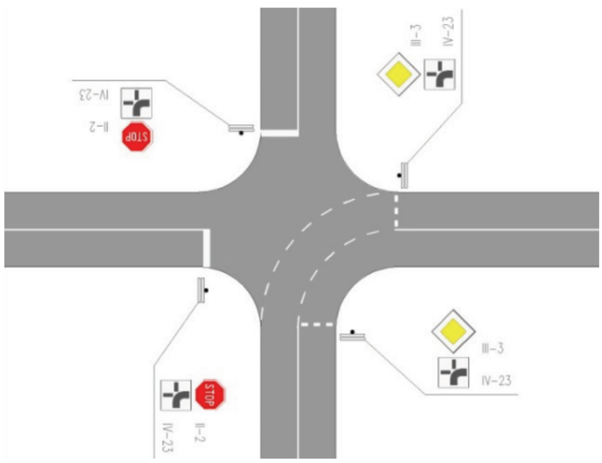


Figure 2 – Typical 4-leg non-standard TWSC intersection

Unique traffic signs are designed to define the priority at NSUIs, indicating the path of the major road [7].

3. RESEARCH BACKGROUND

Gap acceptance at TWSC intersections has been the subject of research since 1965. In the Road Research Laboratory (England) model [8], the sizes of major road streams and headways required to perform minor movements are used to calculate their capacity. These values are given roughly, with a minimum critical headway of 8 s.

In the HCM 1985, a model for the capacity calculation is given for each manoeuvre. This model uses critical headways in the major stream to calculate capacity. These values are separated by the major stream vehicle speed (50 or 80 km/h) and the number of major road lanes [9].

The HCM 1994 [10] defines the "minor movement capacity" and the values of the follow-up headways that appear in the formula for the capacity calculation. The headways values are given according to the manoeuvre being performed, while the vehicle speed in the major stream is not considered. Capacity in the HCM1994 is calculated according to the model developed in Germany [11].

In the HCM 2000 and the HCM 2010 / HCM 2016, the basic formula for the capacity calculation was changed. The Harders formula [2] was used instead of the Siegloch model, with the same fundamental values: the conflict flow, the critical headway and the follow-up headway.

Several papers have been published on gap acceptance and headway values. In their papers, Brilon [12] and Hagring [13] gave recommendations on procedures for evaluating critical headways. Kittelson and Vandehey [14] assessed the impact of gap acceptance on minor movements delays. Daganzo [15] estimated the gap acceptance parameters obtained from field measurements. Hewitt [16, 17] analysed how critical headways (gaps) can be most reliably measured and gave a model for estimating these values using probabilities [18].

Many other researchers have been looking for ways to determine the size of critical headways and follow-up headways based on field measurements and statistical analysis to evaluate their values [19–23].

The headway values for unsignalised intersections and capacity analysis for connected and automated vehicles were analysed in the papers written by Chen and Liu [24] and Linheng et al. [25].

Despite many studies on the topic of headways, the largest number is related to the standard TWSC intersections, while NSUIs are completely neglected. That could be because the NSUIs are generally less represented on road networks and have lower traffic volumes than standard ones.

The main topic of the research conducted by Gattis and Low [26] was the values of critical headways at the NSUI. The values were not measured in the way proposed by the HCM, so the applicability of such results is unclear. According to the intersection streams (*Figure 3*), as shown in *Table 1*, headways were measured in two stages. Values were obtained only for the east approach in the first stage: movement 5 – through from the eastern approach and movement 4 – left turn from the east approach. Values were measured for the south and east approaches in the second stage: movement 9 – right turn from the south approach and movement 4 – left turn from the east approach. The values obtained are sorted by the measurements without clearly defining the headways for every movement.

This way of measuring values shows the critical headway of vehicle movement on the major road but does not mention anything about the value of the follow-up headways on the minor road. Another objection to this way of determining the headways is that a critical headway was obtained for stream 5, which is defined as a major stream. For this reason, values given in *Table 1* cannot be used to calculate capacity at the NSUI, according to the HCM procedure.

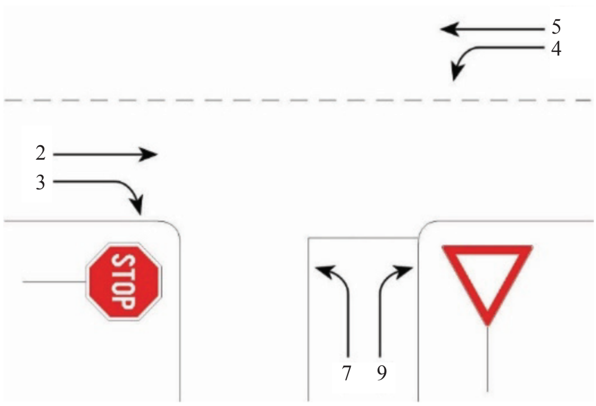


Figure 3 – Non-standard intersection analysed in Gattis and Low research

Table 1 – Measured critical gaps/headways in Gattis and Low research

Vehicle movement	Critical gap t_c [s]
Through traffic from Westbound (movement 5)	3.3
Left turn from Westbound (movement 4)	6.0
Right turn from Northbound (movement 9)	7.8
Left turn from Westbound (movement 4)	6.6

Although the headways were not measured according to the HCM method, some movements may require a significantly different headway from the SUI recommendations.

Two papers which analyse conflict flows and critical gaps at non-standard unsignalised intersections were written by Slovak researchers Pitlova and Kocianova [27, 28].

A paper written by Bogdanovic et al. [6] conducted pilot research on several 3-leg NSUIs and gave preliminary values of critical headways, while the follow-up headways were taken from HCM. That paper showed that driver behaviour at NSUIs differs from behaviour at SUIs, which is reflected in the values of critical headways.

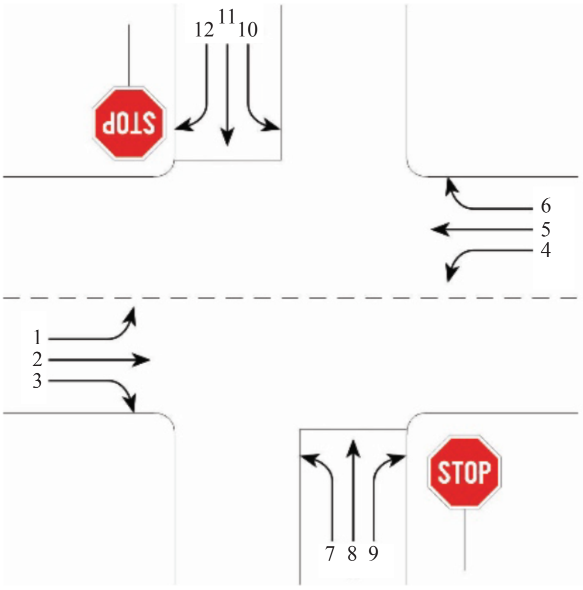
4. GAP ACCEPTANCE AT THE NSUIS

In this chapter, definitions of measured values are given.

4.1 Ranks and movements at the NSUIs

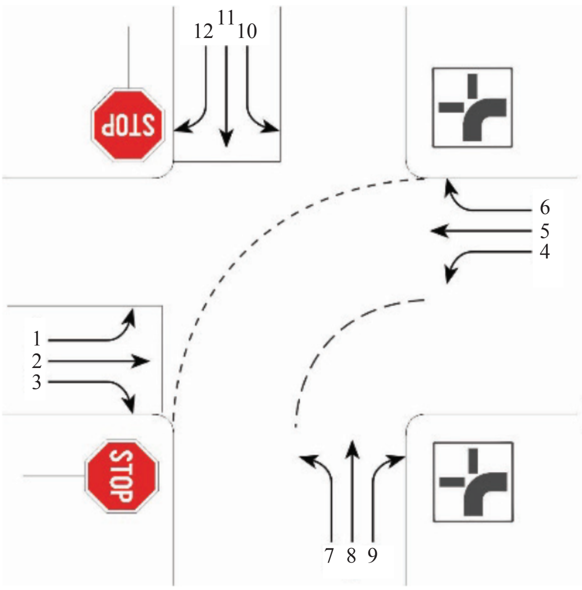
To define movements and ranks at the typical NSUI, a 4-leg intersection with usual geometry (all approaches at the right angle) was analysed. At this intersection, traffic is regulated in a typical way for the NSUI. The following figures show the typical 4-leg intersections. *Figure 4* shows a standard TWSC intersection, while *Figure 5* shows a 4-leg NSUI. Traffic streams at both intersections are defined in the same way to make it possible to identify differences and make comparisons.

The main difference in ranks between a standard and non-standard unsignalised intersection is caused by the fact that two major and two minor approaches are next to each other at the NSUI. There is a subordination between the east and south approaches and the north and the west approaches



Rank	Traffic stream
1	2, 3, 5, 6
2	1, 4, 9, 12
3	8, 11
4	7, 10

Figure 4 – Streams and ranks at the standard 4-leg unsignalised intersection



Rank	Traffic stream
1	4, 5, 6, 9
2	3, 7, 8
3	1, 2, 12
4	10, 11

Figure 5 – Streams and ranks at the non-standard 4-leg unsignalised intersection

caused by the right-hand traffic rule. Namely, vehicles from the north approach are obliged to give way to the vehicles from the west approach, while the vehicles from the south approach are required to give way to the vehicles from the east approach.

Table 2 – Minor movements at 4-leg NSUI

Movement number	Type of movement	Rank
8	Through traffic on approach 2	2
7	Left turn from approach 2	2
3	Right turn from approach 1	2
1	Left turn from approach 1	3
2	Through traffic on approach 1	3
12	Right turn from approach 4	3
11	Through traffic on approach 4	4
10	Left turn from approach 4	4

To determine the priority of minor movements, the "MINOR NORTH" and the "MINOR WEST" approaches were defined in papers written by Ruskic [29] and Bogdanovic et al. [1]. Consequently, there are eight different minor movements at the NSUI, unlike the SUI, where four types of minor movements exist.

Consequently, because of eight minor movements, there are eight different critical headways and eight different follow-up headways.

4.2 Data collection

In order to measure headways, several intersections were selected for the survey. There were 20 NSUIs in different-sized cities (from 5,000 inhabitants – Irig, Serbia to over 1,500,000 inhabitants – Belgrade, Serbia), different geometries (3-leg and 4-leg) in two countries – Serbia and Bosnia and Herzegovina. The following were selected for the data collection:

- 12 cities (7 in Serbia and 5 in Bosnia and Herzegovina)
  (SRB) Šabac – 2 intersections
  (SRB) Sremska Mitrovica – 6 intersections
  (SRB) Beograd – 2 intersections
  (SRB) Irig – 1 intersection
  (SRB) Kikinda – 1 intersection
  (SRB) Niš – 1 intersection
  (SRB) Novi Sad – 1 intersection
  (BiH) Brčko – 1 intersection
  (BiH) Bijeljina – 1 intersection
  (BiH) Tuzla – 1 intersection
  (BiH) Prijedor – 2 intersections
  (BiH) Doboj – 1 intersection
- 20 intersections, of which:
  6 four-leg
  14 three-leg.

The main criteria were that traffic streams at the major and minor approaches must be intensive to achieve as many critical intervals as possible and obtain the most realistic values. For that reason, analyses were conducted in peak hours. Peak hours were determined by traffic counting and recorded by selecting one to three hours with most intensive traffic flows. All intersections were recorded by digital camera. The duration of each recording was from 1:00 h to 3:00 h.

Figure 6 – Video analysis of recorded material

Every interval was measured in relation to a fixed point (traffic sign, light post, line or arrow of horizontal marking). The passing of the first vehicle over or near the fixed point was the start of the interval measurement, while passing of the following vehicle was the end of the interval. For this purpose, the KM Player was used for measurements of headways, because of its accuracy. Namely, the KM Player can measure time with an accuracy of 0.001 s, which was more than enough for critical headway and follow-up headway analysis.

5. RESULTS

The total sample of the critical headways was 3,436, of which 1,044 were at four-leg while 2,392 were at the three-leg NSUI. The follow-up headways sample was 742, of which 519 were at the three-leg while 223 were at the four-leg NSUI. The collected data were processed according to the maximum likelihood procedure using maximum rejected and minimally accepted headways [30]. The values obtained after processing are given in *Table 3*.

The above table shows differences in values measured at intersections of different geometries. Almost all values of critical intervals are generally larger at 4-leg than at 3-leg intersections. These differences can be seen at minor approaches, where, due to the complexity of the manoeuvres at 4-leg intersections, both headways are larger than at 3-leg NSUI.

The values obtained by surveying at the NSUIs are significantly different from those recommended for the SUIs in the capacity analysis manuals. Although there are eight minor movements at the NSUI, compared to the four at the SUI, four exist at both intersections, and they can be compared. The following table shows the difference between the values recommended in the HCM 2000/2010/2016 for the SUIs and measured values for the NSUIs.

Table 4 shows a significant difference in headway values between the SUIs and the NSUIs. Critical headways are larger at the NSUIs, and follow-up headways are smaller than at the SUIs. The reason for these differences is that vehicle speeds at the NSUIs major approaches are lower than the speeds of the SUIs major approaches due to their turning in the centre of the intersection. The lower value of the critical headway for stream 3 – right turn from the minor approach and stream 10 – left turn from

Table 3 – Calculated values of critical headways and the follow-up headways at 3-leg and 4-leg NSUI

Stream	3-leg NSUI		4-leg NSUI	
	Critical headway t_c [s]	Follow-up headway t_f [s]	Critical headway t_c [s]	Follow-up headway t_f [s]
1	–	–	6.3	3.4
2	6.5	2.8	6.9	3.2
3	5.2	2.4	5.5	2.7
7	5.6	3.3	6.3	3.4
8	7.6	2.6	7.6	2.8
10	7.7	3.2	7.8	3.2
11	5.8	2.9	6.4	3.2
12	–	–	5.5	2.7

Table 4 – Comparison of $t_{c,base}$ and $t_{f,base}$ values at the SUIs and the NSUIs for two-lane major road

	Base critical headway $t_{c,base}$ [s]		Base follow-up headway $t_{f,base}$ [s]	
Intersection / Movement	Standard unsignalised intersection	Non-standard unsignalised intersection	Standard unsignalised intersection	Nonstandard unsignalised intersection
Left from major	4.1	6.3	2.2	3.4
Right from minor	6.2	5.5	3.3	2.7
Through from minor	6.5	6.9	4.0	3.2
Left from minor	7.1	6.5	3.5	3.2

the minor approach indicates that drivers from these approaches have better visibility compared to the SUI. Also, lower vehicle speeds at the major road in the left and the right turn make drivers in these approaches to accept smaller headways. According to traffic regulation, other values of the critical headway intervals are expected to be higher.

Follow-up headways differ significantly, and they are generally smaller than at the SUIs. This difference is also related to speeds and visibility at the NSUI. The only value that deviates is movement 7 – left turn from the major approach, which is about 1.2 seconds higher than the value on the SUI. This value is conditioned by constant vehicle deceleration due to their reduced visibility to the right, from where vehicles appear in the prior stream. During surveys, it was observed that drivers turning to the left from the priority approach reduce their speed and even stop their vehicle sometimes to check if there is a vehicle on their right side.

6. VALIDATION OF THE RESULTS

In order to validate the measured results, an intersection with a very high traffic volume at the minor approach was selected. The selected intersection had a constant queue at a minor approach (streams 2 and 3).

According to the methodology given in paper [1], the capacity calculation was made using the procedure from this research.

Conflict flow for stream 2:

$$V_{c,2} = V_4 + V_7 + V_9 = 598 \text{ veh/h}$$

Critical headway and follow-up headway: $t_{c,2}$=6.5 s, $t_{f,2}$=2.8 s.

Potential and movement capacity:

$$C_{p,x} = C_{m,x} = V_{c,x} \cdot \frac{e^{-V_{c,x} \cdot t_{c,x}/3600}}{1 - e^{-V_{c,x} \cdot t_{f,x}/3600}} = 546 \text{ veh/h}$$

The theoretical capacity for stream 2 was: $C_{T\text{-}2}$=546 veh/h.

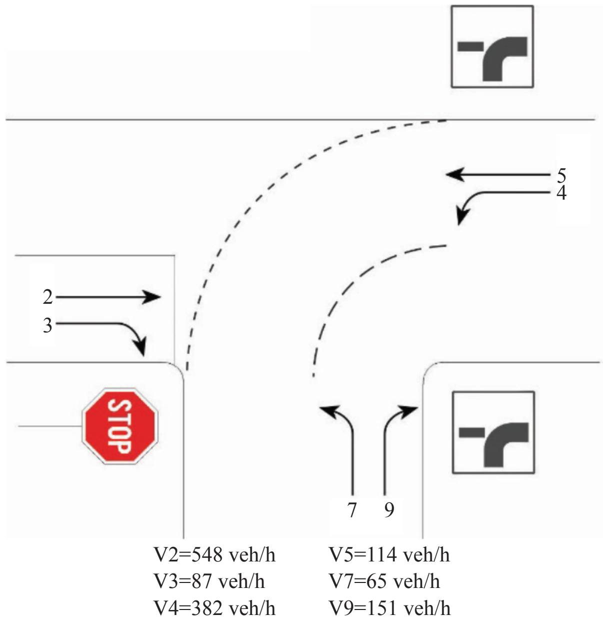


Figure 7 – Streams at the analysed 3-leg NSUI

The movement capacity for stream 2 is defined as a counted number of vehicles entering the intersection because of the constant queuing conditions. The movement capacity for stream 2 was: $C_{M\text{-}2}$=548 veh/h.

According to the given values, it can be said that the values given in *Table 3* can be used for the capacity analysis.

7. DISCUSSION

Values of critical headways and follow-up headways at non-standard unsignalised intersections were not determined before. On the other hand, existing values of these parameters determined for standard unsignalised intersections cannot be used for capacity analysis, because of the different positions of major and minor roads. Using the values given in the HCM for non-standard unsignalised intersections can lead to incorrect capacity values for almost all minor approaches. On the other hand,

Table 5 – Recommended base values for the critical and the follow-up headways at the non-standard unsignalized intersections

Minor movement	Critical headway t_c [s]	Follow-up headway t_f [s]
1 – left from minor west *	6.3	3.4
2 – through from minor west	6.9	3.2
3 – right from minor west	5.5	2.7
7 – left from south major	6.3	3.4
8 – through from south major	7.6	2.8
10 – left from north minor	7.8	3.2
11 – through from north minor	6.4	3.2
12 – right from north minor *	5.5	2.7

** movement does not exist at 3-leg NSUI*

some values cannot be taken from the HCM, because they are not defined (such as minor movement 2, minor movement 3…).

In this paper, comprehensive research of critical headway and follow-up headway at non-standard unsignalised intersections was conducted. According to the measurements in real traffic flow, critical headway and follow-up headway values were determined. The recommended values are given in *Table 5*.

Since the factors which can influence values at 3-leg intersections have not been analysed in this paper, it is recommended that all values, both the critical and the follow-up headways for the minor movements, should be reduced by 0.2 s at the 3-leg NSUIs.

The results obtained by this research can be applied at intersections with typical geometry (streets intersect at a right angle or close to a right angle).

The determined values represent base values, while influence factors are not determined in this paper. Further research should focus on factors that can influence critical headway and follow-up headway values, such as heavy vehicles, grades and other factors.

8. CONCLUSIONS

Unsignalised intersections can be standard or non-standard. The main difference is in the way of regulation of traffic flows in the centre of the intersection. For capacity analysis, three major factors should be determined (conflict flow, critical headway and follow-up headway). All of them are different at non-standard unsignalised intersections compared to standard unsignalised intersections.

By analysing the existing references related to the unsignalised intersections, it was found that there are no determined values for critical headways and follow-up headways at non-standard unsignalised intersections. Besides, the values recommended by the HCM cannot be used for capacity analysis of NSUIs.

In order to obtain realistic values for critical headway and follow-up headway at NSUIs, on-field research was conducted at several NSUIs in Serbia and Bosnia and Herzegovina. The obtained values showed the following:

- Vehicle follow-up headways at the NSUI are different in number (there are eight headways at NSUI versus four headways in SUI) and value.
- Critical headways in the prior stream differ between the NSUI and the SUI in number (there are eight critical headways at the NSUIs and four critical headways at the SUIs) and in value. As a rule, all critical headways that can be compared are higher at the NSUI than at the SUI.

Using the values recommended by this paper and the model for capacity analysis given in the author's article, capacity analysis of non-standard unsignalised intersections can be done.

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VREDNOSTI PRIHVATLJIVIH INTERVALA SLEĐENJA NA NESTANDARDNIM NESIGNALISANIM RASKRSNICAMA

SAŽETAK

Nestandardne nesignalisane raskrsnice su veoma česte u Evropskim zemljama koje imaju stariju uličnu mrežu. Glavni put često skreće pod nekim uglom u centru raskrsnice, što čini raskrsnicu nestandardnom. Iako su nestandardne nesignalisane raskrsnice veoma rasprostranjene u čitavoj Evropi, pa i u svetu, na temu kapaciteta i intervala sleđenja ovih raskrsnica nema mnogo radova. Uzimajući u obzir činjenicu da se prioritet i konfliktni tokovi na nestandardnim nesignalisanim raskrsnicama razlikuju od prioriteta i konfliktnih tokova na standardnim nesignalisanim

raskrsnicama, može se očekivati da intervali sleđenja nisu nisu isti na nestandardnim i standardnim nesignalisanim raskrsnicama. Posledično, kapacitet na nestandardnim nesignalisanim raskrsnicama nije isti kaon a standardnim. U ovom radu dati su kritični intervali sleđenja i intervali praćenja vozila u sporednom toku na trokrakim i četvorokrakim nestandardnim nesignalisanim raskrsnicama, koji su dobijeni istraživanjem na terenu. U radu su date preporuke koje je potrebno koristiti prilikom analize kapaciteta, kao i poređenje vrednosti intervala sleđenja na standardnim i nestandardnim nesignalisanim raskrsnicama.

KLJUČNE REČI

kapacitet, prioritet, nestandardna nesignalisana raskrsnica, prihvatljivi intervali sleđenja, interval sleđenja, interval praćenja.

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