



Volume 113

2021

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2021.113.2>



Journal homepage: <http://sjsutst.polsl.pl>

Article citation information:

Barchański, A., Żochowska, R. Practical aspects of measuring critical gaps and follow-up times at median uncontrolled T-intersections. *Scientific Journal of Silesian University of Technology. Series Transport*. 2021, **113**, 17-28. ISSN: 0209-3324.

DOI: <https://doi.org/10.20858/sjsutst.2021.113.2>.

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PRACTICAL ASPECTS OF MEASURING CRITICAL GAPS AND FOLLOW-UP TIMES AT MEDIAN UNCONTROLLED T-INTERSECTIONS

Summary. Estimation of critical gaps and follow-up times between vehicles at uncontrolled intersections is an essential step in estimating the capacity of these objects and assessment of traffic conditions. Therefore, measurements of these parameters should be properly prepared and implemented. This paper presents issues related to the performance of field tests at median uncontrolled T-intersection. Measurements included both critical gaps and follow-up times. Based on the collected material, the authors identified problems occurring during traffic observation. Analyzed intersections were located both within and outside built-up areas. Furthermore, this article discusses the influence of selected factors on the accuracy of estimating the critical gaps and follow-up times and formulates the principles of conducting traffic measurements at selected types of intersections.

Keywords: uncontrolled intersection, measurement of traffic characteristics, gap acceptance theory, critical gap, follow-up time

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1. INTRODUCTION

Uncontrolled intersections are common road infrastructure objects, which depending on their location in the spatial structure of the area handle a very diverse traffic flow. For decades, the behavior of traffic participants on such objects has been the subject of empirical and theoretical research. The results obtained allow increasing the accuracy of models describing the traffic flows. Nowadays, analytical and simulation methods are used in this field [1-6].

One of the most important purposes of the survey of traffic at uncontrolled intersections and observation of driver behavior is to determine the capacity of individual movements and assess traffic conditions [1, 7, 8]. The results of the analyses form the basis for assessing whether a given infrastructure solution meets the needs and expectations of users and whether it is sufficient to handle the observed traffic. Based on this, decisions are made regarding the need to upgrade or reconstruct individual intersections. The assessment of the capacity of point and linear infrastructure elements also forms the basis for spatial planning and management at the strategic and tactical level for transport and road network. This confirms the important role of precise estimation of parameters of individual road infrastructure elements in the assessment of parameters of the entire road network of a city, area, or region. Therefore, the results of the intersection field tests provide the basis for the building of the model, its calibration, and constraint formulation. Besides, they allow for the validation of the developed models and for allowing their use in the analysis and description of the phenomena occurring in road traffic [1, 9]. Thus, it is important to pay attention to the problems that may occur when conducting field surveys and to define the rules of conduct when performing traffic parameter measurements such that the error rate is minimized much as possible.

In practice, traffic measurement is a complex research process requiring assumptions, reliable preparation, and conditions that the observed situations must meet to be representative of the population due to the phenomenon under analysis [1, 10, 11]. It is very difficult to meet the requirements of the methods used, considering the random changes in traffic conditions and the individual behavior of traffic participants [1, 9, 12-14]. In the world literature, much attention has been devoted to the analysis of the results of these measurements, the comparison of the efficiency and accuracy of the methods used, and the identification and evaluation of the factors affecting the values of the critical gaps and follow-up times [9, 11, 15-17]. However, there is a lack of research on how to conduct measurements and the problems associated with it, which are largely due to the specificity of the infrastructure element under study.

Uncontrolled median T-intersections with two two-lane one-way major road carriageways are relatively rare in the road network. They are characterized by specific geometric parameters and traffic organization. Therefore, the critical gap and follow-up time values for these facilities may differ from the values set for the typical uncontrolled intersections. In this situation, there is a need to conduct a separate study of traffic participant behavior by considering the specific characteristics of the intersection.

The main purpose of this paper is to identify problems occurring during the planning and implementation of tests conducted at uncontrolled median T-intersection to estimate the value of critical gap and follow-up time.

This article presents the results of research conducted on selected real objects. The problem of estimating critical gaps and follow-up times at uncontrolled intersections was discussed, with particular focus on the specificity of median uncontrolled T-intersection. The process of conducting observations on selected real objects was described. Finally, the most important recommendations for researching for critical gaps and follow-up times were identified and directions for further research were indicated.

2. CONDITIONS FOR CONDUCTING RESEARCH OF CRITICAL GAPS AND FOLLOW-UP TIMES AT UNCONTROLLED INTERSECTIONS

Models to estimate capacity and assessment of traffic conditions are mainly based on the gap acceptance theory. It singles out the most important parameters: the critical gaps and follow-up times. Their values depend on the type of intersection and allow the model to be calibrated to local conditions. They are estimated using statistical analysis in a representative sample of recorded traffic situations [16-19].

Critical gaps and follow-up times generally characterize the average behavior in the population of drivers of a given movement. The critical gap (t_g) corresponds to the minimum value of the time gap between the passage of two consecutive vehicles of the major stream accepted by at least half of the tested sample of drivers [1, 9, 14, 18, 20]. The follow-up time (t_f), on the other hand, is determined as the average time interval between the crossing of the stop line by two consecutive minor stream vehicles in the subordinate movement during the gap in the major stream. An extensive description of the concepts used and the assumptions of the model used can be found in [14, 15].

To guarantee the correctness of critical gap studies and standardize the results obtained, the observed traffic must meet the assumptions adopted in the construction of the models used to estimate the critical gaps and follow-up times and correspond to the conditions and limitations of the methods for capacity estimation and assessment of traffic conditions [17-19, 21]. They define the ideal conditions for vehicle traffic at the intersection at the time of the study, including [1, 9, 12-14]:

- homogeneous traffic consisting only of passenger cars in all streams,
- the presence of only two conflicting movements: the first rank stream and the studied subordinate movement,
- free-flowing traffic with a steady first-order stream passing the conflict zone straight through without impedance, delays, or slowdown,
- a permanent queue of vehicles of a given subordinate movement waiting to continue their trip,
- independent, random oncoming at the approach of vehicles of the major stream without platoons,
- the absence of other factors not mentioned above such as pedestrian or bicycle traffic, impedance, bus stops, and the impact of upstream signalized intersections.

A commonly used method of estimating the values of critical gap and follow-up time is the observation of real traffic on objects selected for the analysis, considering the time between the passage of successive vehicles or by measuring the distance between individual, successive vehicles. Many diverse models and ways of description have been developed in this area [9, 10, 16, 19, 20, 22, 23].

Researching real traffic conditions with the need to meet the assumptions of the method used, involves the need to solve many practical problems resulting from the variation of traffic conditions between the requirements of the model and reality [17-19, 21]. It is most important to identify them early and take corrective action before the actual analysis begins. On real objects, pilot studies should be conducted before starting the analysis to be acquainted with the drivers' behavior and to choose the most appropriate observation point location. The field constraints [1, 12-14] should be considered.

It is necessary to analyze the situation in the whole area of the intersection during a single gap in the major stream. This approach is necessary to be able to correctly interpret drivers' behavior and assess whether the observed situation meets the requirements of [9, 16, 17, 20]. This creates some difficulties in the process of automation of measurements and data analysis and the need to playback the recorded footage at least twice.

The problem of selecting an observation point equipped with a camera has received little attention in the literature related to the estimation of critical gaps and follow-up times [10]. Although, it is fundamental to ensure an accurate measurement that is consistent with the actual duration of accepted or rejected gaps as observed by drivers.

The impact of the place of observation on the recording of the starting/ending time of the gap is shown in Figure 1.

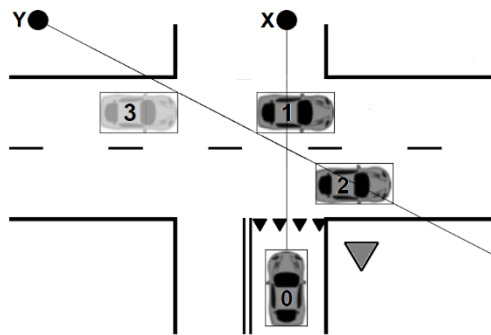


Fig. 1. A way of interpreting the road and traffic situation by two external observers
[Authors' research]

Gap durations recorded from two different points will take different values. Importantly, the magnitude of the gap duration estimation error depends on the order of vehicle movement (labeled 1 and 2) in each lane of the major stream.

Equally important is the choice of the observation point due to the temporarily reduced visibility of the traffic situation at the intersection by vehicles moving on the far lane, closest to the location of the recorder. It is advisable to seek locations in the immediate area that minimize this effect. In addition, the adverse effect of limiting visibility can be partially mitigated by delineating certain virtual cross-sections perpendicular to the axis of the lanes, the crossing of which by vehicles will determine the beginning or end of the gap. To keep the adoption of these cross-sections unambiguous and constant, they should be based on fixed elements in the intersection area. Given the need to ensure continuous visibility of the characteristic points when the traffic situation and the momentary position of vehicles changes, it is important to have them located as close as possible to the collision points.

For accurate results, it is advantageous to conduct observations from high altitudes, where the object becomes approximately two-dimensional and a single camera is sufficient to record the entire face of the intersection and all movements. It is worth mentioning that it would be good practice to locate the observation point in a manner which in addition to monitoring the most important elements from the point of view of the analysis purpose, fragments of road sections of the subordinate and major approach are also visible so that it is possible to observe the queue of waiting vehicles and oncoming traffic as well.

Example combinations of the passage of subsequent vehicles of the first rank stream influencing the acceptance of the available gap in relation CL1 (Class 1) are shown in Figure 2, presenting the relevant part of the intersection for a given relation.

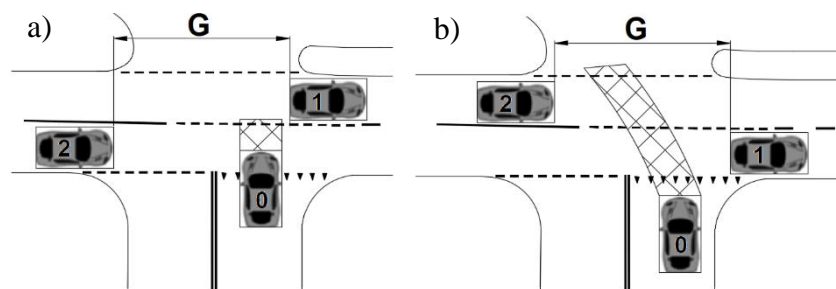


Fig. 2. Influence of the major stream's vehicle passing sequence on the decisions made by drivers of vehicles waiting at the subordinate approach:
 a) accepted gap; (b) rejected gap; G – gap duration
 [Authors' research]

The hatched area marked on the diagrams (Figure 2), denotes the conflicting portion of their traffic corridors on the intersection face shared by the superior and subordinate streams. Due to the different size of the conflict zone required by the vehicle of the subordinate relation in both situations, the crossing time will be different, that is, shorter in situation a than in situation b. Although the measured duration of G-gaps according to the definition will be comparable in both situations, the probability of their use by drivers will differ.

3. CHARACTERISTICS OF MEDIAN UNCONTROLLED T-INTERSECTIONS

The subject of the analysis was the time intervals between vehicles at the median uncontrolled T-intersections and two two-lane one-way major roadways. In manuals, these intersections are treated similarly to 1x2 road crossings or four-way intersections with a wide median strip, and capacity analyses are conducted using commonly used methods such as MOP SBS, HBS, or HCM [12-14]. However, the specific characteristics of these facilities require a different approach to the planning and implementation of field traffic measurements [1]. The dissimilarity of these types of objects is confirmed by the results of the analyses of the hierarchy of movement, the influence of impedance, and how the different movements are performed [1, 12-14, 16, 17, 19]. Therefore, the values of the critical gaps and follow-up times contained in the indicated instructions do not apply to this type of intersection.

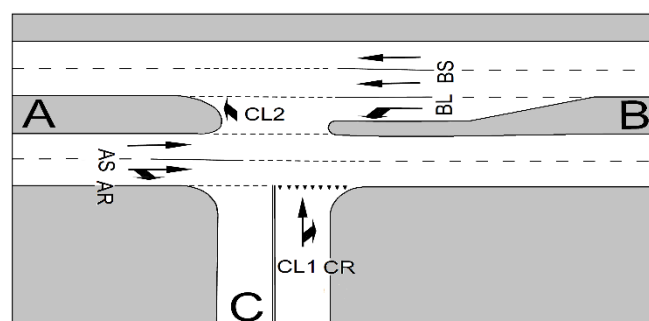


Fig. 3. General diagram of a median uncontrolled T-intersection with the indication of traffic flows
 [Authors' research]

Both the geometric layout of the examined type of intersection and the traffic organization is shown in Figure 3. The most characteristic feature of the studied type of facilities is the presence of a wide dividing median strip. This element, together with the two two-lane carriageways of the major road, determines how the vehicles of the subordinate movements make their maneuvers, the amount of superior conflicting stream, the number, and how the superior streams are observed. The presence of a wide dividing median strip accommodating one vehicle makes the left turn maneuver executed in two stages. Thus, to estimate the values of the critical gap and follow-up times, it has been divided into two separately considered maneuvers, CL1 and CL2 (Class 2) [1, 9, 19, 24, 25].

Some of the maneuvers of the subordinate movements, that is, turning right from the subordinate approach (CR) and turning left from the major road (BL- Back left), are similar to the corresponding maneuvers at the 1x2 type road intersection. Minor differences may only be due to the number of lanes of superior movements and their traffic flow [1, 12-14, 25].

4. DESCRIPTION OF SURVEYS CONDUCTED ON SELECTED REAL SUBJECT INTERSECTIONS IN A SPECIFIC LOCATION

Problems occurring during measurements for estimating critical gaps and follow-up times were identified based on the experience gathered from the survey conducted in 2018 at two selected intersections located in the Metropolis GZM (in Polish: Górnośląsko Zagłębiowska Metropolia) – the metropolitan area in the Silesian Voivodeship. Figure 4 shows the location of the study intersections.

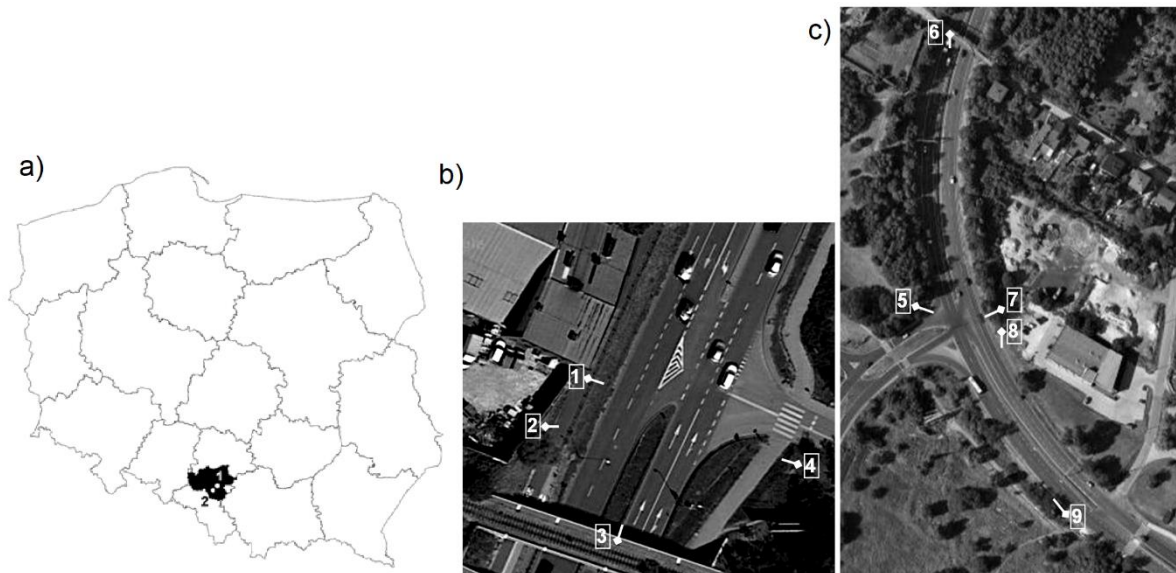


Fig. 4. Location of the tested objects with the indication of the measurement sites:
 a) the location of the subject intersections in the background of the administrative division of the country and the GZM metropolis, b) View of object No. 1 (within the built-up area),
 c) View of object No. 2 (outside built-up area)

[Authors' research]

The first object is located in one of Katowice's downtown districts and handles through, inbound and outbound traffic in the city. The southern alignment of the major road provides one of the few connections between the southern and northern districts and the city center. The minor road is of local significance, although a significant increase in traffic volume is observed throughout the object during peak hours. The immediate environment has diverse socio-economic functions. Commercial and service facilities, low-rise residential buildings, production plants, and warehouses are located here.

Research object No. 2 is located outside the built-up areas; however, in the area of influence of large agglomerations, in the administrative area of the city of Mikołów (Silesian voivodeship). The major road is a regionally important connection of urban centers, running to the borders of the voivodeship. The minor road provides access for city residents to important thoroughfares in the area and runs through the entire urban area of the city. The intersection serves the through traffic characterized by a significant size of traffic streams in all movements. The proximity of large agglomerations generates trips in many motivations and directions. In the immediate vicinity, there are homogenous, dense low-rise buildings, service and commercial points, and forest areas.

Both facilities are effectively separated from their immediate surroundings, and there is no influence from pedestrians or other factors that could interfere with the traffic conditions necessary to determine the critical gaps and follow-up times.

As part of the pilot survey and analysis of the immediate surroundings of the objects in a specific location to find the best available observation points, while aiming to minimize the number of cameras required, attempts were made to record from several potentially attractive locations. The locations in the area of intersections are shown in Figure 4. White squares indicate the location of the observation point in the surroundings of the intersection face and the segments coming out of them in the direction of registration in the axis of the camera. The view of the intersection face from cameras placed at all surveyed measurement locations is shown in Figure 5.

In Figure 5, the view from the places selected for the main surveys shows the location of the virtual cross-sections used to determine the start and end times of the gaps - the dotted lines are used to study the major streams, while the lines of the "dot-dash" type - the subordinate movement. A study of the CL2 movement was conducted from point 6. The virtual cross-section for the superior stream was determined based on the presence of a vertical sign located at the edge of the wide dividing strip, while for the subordinate stream - based on a dashed line separating the major road lanes from the entry slip road. The same principles were applied when analyzing the CR³ movement using observation point 8. The CL1 and BL movements were examined from observation point 7. The virtual cross-section for the superior stream identical for both maneuvers was determined based on the vertical sign remaining in line with the apex of the excluded surface separating the carriageway on the subordinate road. However, for subordinate streams, these are the unconditional stop lines and the wide dividing strip limit line.

Before conducting the main research, it is necessary to analyze the driver behavior occurring at the intersection, its proper classification, and aggregation. It is necessary to make assumptions, defining which situations will be used for research and which will be rejected. Although it may seem that the law regulates the way of moving in the intersection area, practice shows that each situation is different, and sometimes inconsistent with generally accepted rules, which for the studied objects is presented in Figure 6.

³ CR – turning right from the subordinate approach C



Fig. 5. View of the studied intersections with potential observation points
[Authors' research]

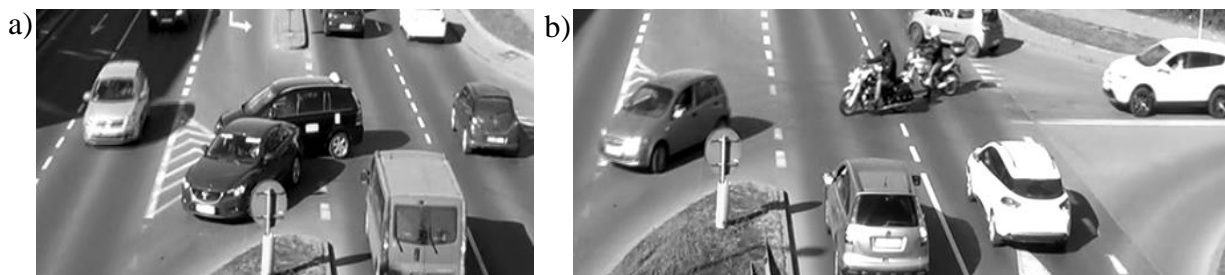


Fig. 6. Examples of different ways of creating a queue of vehicles in CL2 movement:
a) parallel stops of vehicles; b) a queue built under the assumptions for 1x2 road intersections
[Authors' research]

The most diverse situations were observed in the traffic of vehicles of CL2 movement. Different queuing methods determine the response time required to join the traffic, and thus, causes the resulting critical gaps and follow-up times to vary.

5. IDENTIFICATION OF PROBLEMS OCCURRING DURING SURVEYS OF CRITICAL GAPS AND FOLLOW-UP TIMES AT UNCONTROLLED T-INTERSECTIONS

During the theoretical analysis, the preparation of measurements, and the conduct of research, were identified a set of conditions and problems specific to each subordinate movement. They were formulated independently for the estimation of critical gap and follow-up time. The results are presented in Table 1.

Tab. 1

List of problems identified during the survey of the t_g and t_f times independently for each subordinate movement [Authors' research]

Movement	Problems with estimation of:	
	t_g	t_f
BL	The limitation of the visibility of the superior stream by the CL2 movement vehicles in a wide dividing median strip.	The limitation of the visibility of the superior stream by the CL2 relation vehicles on a wide dividing median strip. In extreme situations, they prevent the movement of BL relations. Diversified trajectories of the movement of subsequent vehicles depending on the place of starting and stopping.
CR	Visibility limitation by a parallel-created queue of vehicles of the CL1 movement.	Two lanes of the major road as destination lane.
CL1	The acceptance of the gap depends on the occupation of the wide dividing median strip. The impact of AR ⁴ vehicles on the available gaps.	Strong dependence on traffic conditions in relation CL2. The decision to execute the maneuver and the trajectory of movement depend on the individual characteristics of the drivers and the occupation of the wide dividing median strip. The impact of AR vehicles on the available gaps.
CL2	The limitation of the visibility of the superior stream by the vehicles of the BL movement. Influence of BL movement vehicles on the gap distribution in the BS ⁵ stream.	Dependence of the entry of subsequent vehicles from the queue on the traffic conditions in CL1 movement. Variation in how more vehicles join and the queue created in the dividing median strip, limiting visibility and maneuverability. Two lanes of the superior carriageway selected as the target line. Impact of BL vehicles.

For each of the subordinate movements, it is possible to estimate the values of the critical gap and follow-up times. The observed traffic must meet the conditions defined in the methods. In practice, however, driver behavior varies widely and it is impossible to draw a clear line between compatible and incompatible situations with the assumptions of the method used. For

⁴ AR – turning right from the approach A on the major road.

⁵ BS – moving straight from the approach B on the major road.

BL movement, the problem of varying trajectories through the intersection is most relevant. In contrast, drivers moving in the CR movement choose one of the two lanes of the major road as their destination lane. When analyzing the CL1 relation, the most significant is the effect of the wide dividing median strip on the variation in the driving behavior of both the first and subsequent vehicles in the subordinate movement. The CL2 maneuver is unlike any other maneuver observed at other types of uncontrolled intersections. This considers both the target lane into which the vehicles will merge and the differentiated entry of subsequent queuing vehicles.

Therefore, it is necessary to make additional assumptions and rules to interpret driver behavior and the extent to which observed traffic situations are used. It is first necessary to identify the traffic situations occurring on a given site and attempt to aggregate them into internally homogeneous groups differentiated from each other to classify driving behavior in the same way during analysis. The last important factor is to clearly define the purpose of the test and the scope of validity of the determined values of the critical gaps and follow-up times, that is, for a specific real object or for a type of object as a whole.

6. CONCLUSIONS

Summarizing the analysis carried out, it should be emphasized that the study of traffic at uncontrolled intersections is aimed at collecting as much information and traffic characteristics as possible to build an accurate model on the studied type of objects to obtain the real behavior of most drivers. This paper points out the necessity of rational planning of critical gaps studies and the preparation for their implementation at median uncontrolled intersections. Nowadays, many different methods are known for testing the values of critical gaps and follow-up times, but in each of them, the observed motion must meet a certain set of strictly defined and rigorous requirements. The selected research object should be analyzed in terms of the existing movements, geometry, trajectory and traffic conditions, technical possibilities of traffic registration, and drivers' behavior. The pilot study allows verifying the made assumptions and refining of the way of measuring and setting of the cameras. The final step is to gather a sufficient research sample size.

To ensure high accuracy of the results and precision of the measurements, it is very important to make a proper selection of the observation points, reflecting the traffic situation on the objects exactly as it is in reality and as it is seen by the drivers waiting to crossing or merging the traffic. Observation conducted from a distance, at non-standard angles may falsify the image, introducing distortions in the perception of mutual position of vehicles, and thus, lead to significant errors.

The information contained in this article will be useful for those preparing and planning the implementation of research and traffic observation, especially in the area of intersections, estimation of critical gaps and follow-up times, and those seeking information on traffic conditions and the diversity of real traffic situations.

Furthermore, it is necessary to conduct further in-depth research, although the presented results of the authors' work in an unambiguous, precise, and natural way complements the existing research gap in terms of defining the practical principles and conditions for analyzing critical gaps and follow-up times. In their scope remains the analysis of drivers' behaviors on uncontrolled median T-intersection and the influence of diversified behaviors on the determined values of critical gaps and follow-up times. The biggest challenge will be to develop an apparatus that allows fully automatic determination of the critical gaps and follow-up times.

The software should intelligently interpret the traffic situation, select the situations that meet the assumptions of the method used and properly respond to the problems occurring during the measurements, including those identified in this paper.

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Received 11.09.2021; accepted in revised form 30.10.2021



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