ARCHIVES OF TRANSPORT
Volume 60, Issue 4, 2021

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.5604/01.3001.0015.6030*

ESTIMATION OF CRITICAL GAPS AND FOLLOW-UP TIMES AT MEDIAN UNCONTROLLED T-INTERSECTION

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Abstract:

The efficiency of the entire transportation system depends on the capacity of the individual elements that make up the given network. Point-type elements of the road and street network include intersections of different types. Critical gaps and follow-up times related to individual movements are important determinants of the capacity of such objects. There are many ways to estimate such times. The article discusses the assumptions and scheme one of them - the Siegloch method. The objective of the article is to analyze the process of determining critical gaps and follow-up times at the median uncontrolled T-intersections that are rare in the road and street network and have been studied to a limited extent. The commonly used HCM, HBS, and Polish (MOP SBS) methods in their current form do not consider the specificity of such intersections and thus may not give reliable results. Due to their characteristics in terms of geometry conditions, there is a need for an individual approach to estimate both critical gaps and follow-up times. The article contains the results of empirical research conducted on a selected real object in the Upper Silesian agglomeration in Poland. The intersection under study is located in one of the central districts of Katowice city, in the built-up area serving commercial and service functions. The analysis of the behavior of individual drivers waiting for the possibility to continue driving was conducted separately for each minor traffic movement. The values of critical gaps and follow-up times were determined for all four subordinate movements. The values obtained are different from those contained in the Polish manual, which is recommended for use. The research should be considered as pilot studies that justify the need to develop a separate approach to the estimation of the critical gaps and follow-up times at median uncontrolled T-intersections.

Keywords: *critical gap, follow-up time, uncontrolled intersection, gap acceptance theory, Siegloch method*

To cite this article:

Barchański, A., Żochowska, R., 2021. Estimation of critical gaps and follow-up times at median uncontrolled T-intersection. Archives of Transport, 60(4), 105-124. DOI: https://doi.org/10.5604/01.3001.0015.6030

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1. Introduction

In dense road and street network of the city, the effectiveness of the entire system is mainly conditioned by the capacity of individual intersections. Travel time is an essential criterion for choosing the routes in the network. Therefore, planning traffic flows in a city strictly depends on a detailed analysis of the capacity of individual objects (Brilon et al., 1999; Woch, 2008; Macioszek, 2011; Żochowska, 2014; AASHTO, 2018; Alrawi, 2018). So far, many approaches to estimating the capacity of various elements of the transportation network have been developed. In the most common, such as the reference HCM method, which is the basis for the Polish method, and the German HBS method with a slightly different approach, the process of estimation of capacity is dependent on critical gaps and follow-up times. The indicated variables, together with the conflicting flow rate, are the main parameters of the queue theory model adopted for estimating the capacity (HBS, 2001; GDDKiA, 2004; TRB, 2010; Wu, 2012). The values of these variables should be current, in line with reality, and should reliably reflect the actual behavior of drivers waiting on the minor-street approach. Additionally, it is very important to take into account the impact of the different behavior of individual drivers. The assessment of traffic conditions at intersections, based, among others, on the values of critical gaps and follow-up times, is fundamental for spatial planning of infrastructure objects, their management, and making both strategic and operational decisions in transport (Gerlough & Huber, 1975; Thamizh & Reebu, 2005; Nabaee, 2011; Król, 2012; Żochowska, 2014; Ramu at al., 2015; Abhignai at al., 2016; Chodur & Bąk, 2016; Dutta & Ahmed, 2017; Shaaban & Hamad, 2017; Rao & Gaddam, 2019; Witt at al., 2019; Zacharia at al., 2019).

Methods for estimating the capacity of intersections use a variety of computational schemes. Taking into account the approach to the way of analyzing the observed traffic conditions, these methods can be divided into three main groups: theoretical, simulation, and empirical. The most common of them, theoretical methods, are used in many manuals around the world and may apply primarily to the intersections with typical geometric solutions and traffic organization (GDDKiA, 2004; Akcelik, 2007). They have been developed by adapting queuing theory and probability theory to the description of different traffic situations. Since the lengths of individual gaps in the major stream, as well as the process of arriving the vehicles on the minor-street approach, are stochastic, the specific probability distributions should be used in these models (Gerlough & Huber, 1975; Gavulova, 2012). If in the defined in this way microscopic model, dynamic and non-stationary characteristics are assigned to the adopted parameters, it will be included in the second, an equally extensive group of models, i.e., simulation models. In turn, the experimental approach assumes the analysis of correlations between individual factors determining capacity and then the use of regression models to describe these relationships and processes. Based on such assumptions, the third group of methods, i.e., empirical methods, has been built (Chandra et al., 2014).

To standardize the results obtained when performing various measurements and be able to generalize them, it is necessary to specify the initial conditions that must occur on the given object. The simplest model describes the behavior of drivers in strictly defined traffic conditions of two conflicting streams (major and minor) in the intersection area and it is the basis of the gap acceptance theory, derived from the queuing theory (Abhishek et al., 2019). In this model, it is assumed that the vehicle at the stop line continues to travel if and only if there is a gap greater than or equal to the critical gap in the major stream. If the gap is sufficiently long, it is also used by subsequent vehicles from the queue on the minor-street approach (Weinert, 2000).

To describe the traffic of vehicles of different streams at intersections, the time intervals used to be divided into three groups, which are studied individually (Wu, 2001):

– the time interval between vehicles in the major stream, directly related to the traffic volume,
– the critical gap, indicating the minimum gap between the subsequent vehicles in the major stream, which could be used by the vehicles in the minor traffic streams waiting in the queue to cross or merge the major stream,
– the follow-up time, indicating the time interval between successive vehicles entering from the queue on the minor-street approach in the same gap between vehicles in the major stream.

Each method of estimating the critical gap has individual features. Some groups of methods are based on a common approach and related assumptions.

The comparative analysis and indication of the criteria for the classification of methods is an important and current research problem. Various attributes can be the basis for estimating critical gaps, including (Brilon et al. 1999; Brilon & Wu, 2002; Akcelik, 2007; Vasconcelos et al., 2013; Mohan & Chandra, 2016; Guo et al., 2019; Macioszek, 2019):

– number of vehicles entering each gap,
– accepted gaps,
– rejected gaps,
– accepted lags,
– rejected lags,
– maximum rejected gaps.

In terms of the calculation techniques used for estimating the critical gaps and follow-up times, multiple regression models, neural networks, binary logit models, support vector machines, or different iterative approaches should be mentioned. Some of these methods are simpler in terms of computation, while others can only be solved with the use of IT tools. The conceptual differences between them result in the obtaining of various values for the estimated critical gaps.

The authors of the article attempted to estimate the critical gaps and follow-up times at median uncontrolled T-intersection (MUT-intersection) with major two-lane roadways. This type of intersection is not widely investigated and described in terms of the estimation of its capacity as well as critical gaps, and the guidelines for estimating the capacity of intersections recommend the use of standard calculation procedures for this type of object, without taking into account their specificity in terms of geometric conditions and traffic organization (Patil & Pawar, 2015). The article aimed to analyze the process of determining the critical gaps and follow-up times at the MUT-intersection according to the Siegloch method. One of the objectives of the study was also to compare the values of the critical gaps and follow-up times included in the Polish manual for estimating the capacity of uncontrolled intersections with the results of empirical research.

The article consists of 6 sections. The first section presents the purpose of the research and the current state of the issue. Section 2 describes the analyzed type of intersection and discusses the features that make it different from other types. The Siegloch method with the scheme covering individual stages and an indication of the advantages and disadvantages of the adopted approach is presented in Section 3. It also contains the assumptions and conditions necessary to meet and a formal description of the method. Section 4 presents the results of research on the critical gaps in the major stream and the follow-up times between vehicles awaiting at the minor-street approach carried out under real conditions at a selected intersection located in the built-up area of the Upper Silesian agglomeration. The results were compared with the values recommended by the Polish manual used to estimate the capacity of uncontrolled intersections. In Section 5, the obtained results are discussed and their influence on the potential capacity is examined. The article ends with conclusions and directions for further research.

2. The median uncontrolled T-intersection

MUT-intersections occur quite rarely in the road network and due to many various structures of these objects and their location in different areas, each of them is characterized by various features (Barchański, 2020). The objects of the examined type, due to their significant difference from other types of uncontrolled intersections, require individual analysis of the hierarchy of existing movements and their subordination (Gaca et al., 2011; Mohan & Chandra, 2016; Dutta & Ahmed, 2017; AASHTO, 2018). It should be noted that these objects are not sufficiently described in the publicly available literature and require more detailed research in the field of estimation of both the critical gaps and follow-up times. Fig. 1 presents the traffic organization at this type of intersection.

The objects under study are mainly located on high-speed roads. They are usually shaped according to local needs and without additional carriageways or ramps. This type of intersection has a clear structure and traffic organization, which enables leading traffic on the major road much more efficiently (i.e., without delays) than in the case of the intersections with traffic lights. In addition, the median allows two-step crossing of the intersection, which makes it easier for drivers from the minor traffic movement to cross or merge the traffic while ensuring the appropriate level of safety (Komar & Wołek, 1993; Gaca et al., 2011). Improving traffic conditions and increasing safety is also achieved by distributing the traffic volume on the major road into two roadways, reducing the impact of some traffic streams, and improving visibility by reducing distraction and dazzling drivers caused by the vehicles from the opposite direction. Additionally, the channelization of the traffic flows, resulting in a narrowing of the area that conflicts with other traffic movement and appropriate control of the conflicts of the individual flows, reduces the number of necessary decisions made by the driver. As a result, at these intersections, drivers can concentrate more on the maneuver being performed (Gaca et al., 2011; Chodur & Bąk, 2016; AASHTO, 2018; Abhignai et al., 2020).

There are only three levels of the priority of streams at the MUT-intersections. Vehicles of the major traffic movements, i.e., going straight (AS, BS) and turning right (AR) from the major road, drive through the intersection without delays. All other movements are minor traffic movements, and it is possible to set critical gaps and follow-up times for them. The left turn from the major-street approach (BL) and the right turn from the minor-street approach (CR), as well as the second stage of the left turn from the minor-street approach (CL2), are classified as second-rank streams on a given type of intersection. The maneuver of crossing the major road while turning left from the minor-street approach (CL1) is the lowest level of the streams. Both the CR and the BL movements can be considered classically, while for the left turn the need to cross two lanes on the major road is associated with a longer clearing time, which must be considered by drivers (HBS, 2001; GDDKiA, 2004; TRB, 2010; Gaca et al., 2011).

Although the Polish method includes a dedicated two-step procedure for estimating the capacity of intersections with median, it has been developed mainly for four-leg intersections. Its application to MUT-intersections is limited due to differences in the impact of conflicting traffic streams. The comparison of conflicting traffic streams for a left-turn movement from a minor-street approach at both types of objects is presented in Fig. 2.

The drivers turning left at the second stage (marked CL2 in Fig. 2) merge the traffic and observe the part of the stream going straight from the B approach occurring only in the left lane. This behavior is different from what is assumed in the HCM, HBS, and Polish method, where the critical gaps are determined as for the left turn from minor-street approach, in which drivers have to observe the streams of four different higher-ranked movements (HBS, 2001; GDDKiA, 2004; TRB, 2010).

Due to the existence of only one minor-street approach, vehicles may stop in the median area at MUT-intersections at other places than at four-leg intersections, as shown in Fig. 2. This affects the possibility of making the first stage of the left turn from the minor-street approach impeded by the left-turn movement from the major-street approach. Unlike at the four-leg median intersection, where the second stage of a left turn from the minor-street approach is impeded. This difference can be seen in Fig. 3, which shows the conflict points and the path for all movements at the intersections.

At the four-leg median intersection, the BL movement impedes in the second stage. However, at MUT-intersections, this occurs at the first stage of a left turn from the minor-street approach, which was not taken into account in determining the conflicting flow rate in the Polish method. There are no dedicated calculation formulas in the Polish manual that would determine the strength of the impact of individual streams through adjustment factors (Brilon, 2009; Patil & Sangole, 2015; Pawar et al., 2015; Tanackov et al., 2018; Abhignai, 2020).

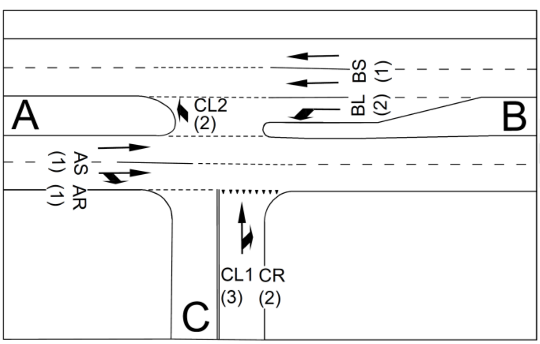

Fig. 1. Scheme of the MUT-intersection (numbers in brackets show the rank of each movement) [own research].

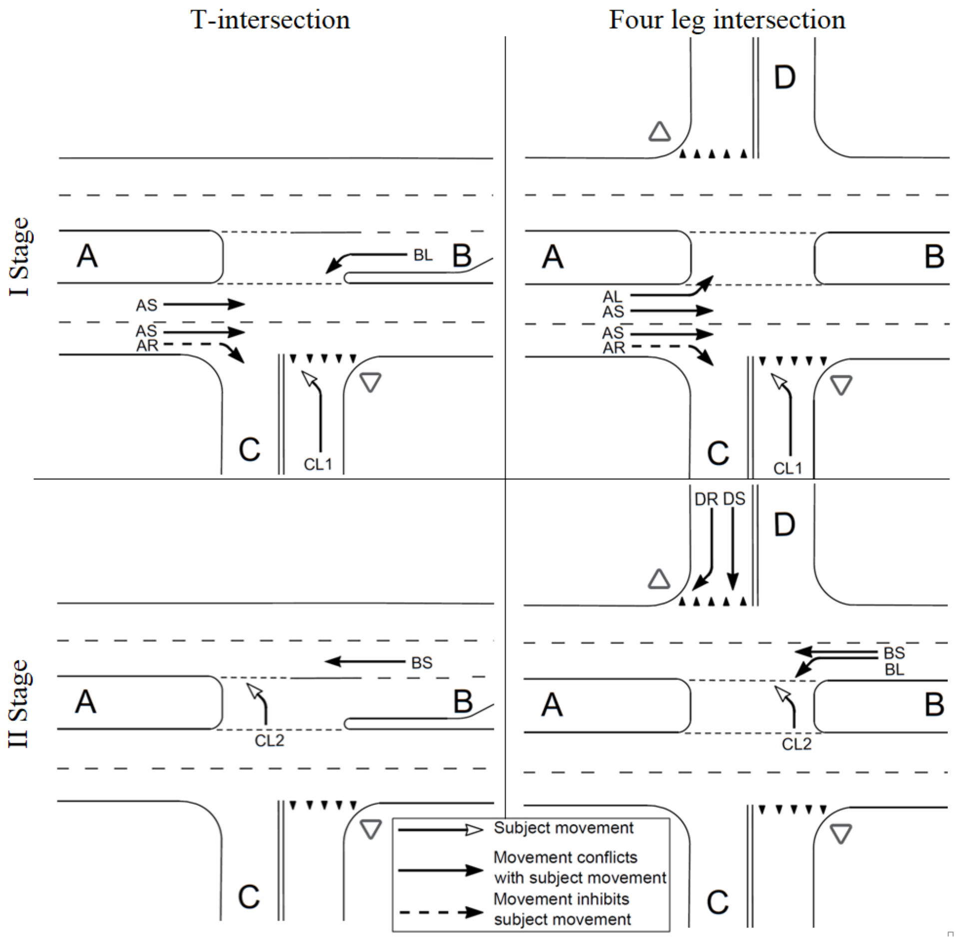

Fig. 2. Comparison of movements conflicting with left-turn movement from minor approach between three and four-leg median intersection [own research]

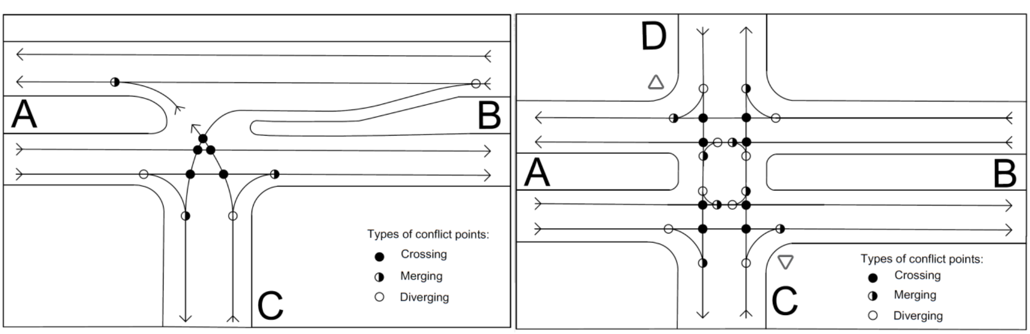

Fig. 3. Comparison of conflict points between three- and four-leg median intersection [own research]

3. Methodology

3.1. General assumptions of the method

The traffic of vehicles may be considered equivalently in terms of time or distance, as shown in Fig. 4, which presents the relationship between the headway and the gap at the MUT-intersection with two major two-lane roadways (Gaca et al., 2011; Barchański, 2020). Drivers waiting at the minor-street approach observe the subsequent vehicles moving in the major stream and the available time gaps between them. The gaps can be rejected or accepted by drivers to merge or cross the traffic. The headway H_T shown in Fig. 4 indicates the time interval between passing the measurement section by a fixed body component of two successive vehicles. In turn, the gap G_T is measured as the time interval in which there is no body element of two subsequent vehicles in a fixed measurement section, perpendicular to the axis of the major road. According to Raff's definition, the critical gap is the minimum time gap in the major stream accepted by the second quantile of the driver population (Gerlough & Huber, 1975; Ashalatha & Chandra, 2011; Gavulova, 2012). An important parameter is also the residual gap (lag) L_T, which corresponds to the time remaining to reach the measurement section by the nearest oncoming vehicle on the major road, where this section is determined by the axis of symmetry of the vehicle waiting on the minor-street approach. The follow-up time HQ is the time elapsed between the crossing the stop line by a fixed body element of two subsequent vehicles awaiting in the queue using the same gap in the major stream to cross or merge the traffic (Gerlough & Huber, 1975; Brilon at al., 1999; Barchański, 2020).

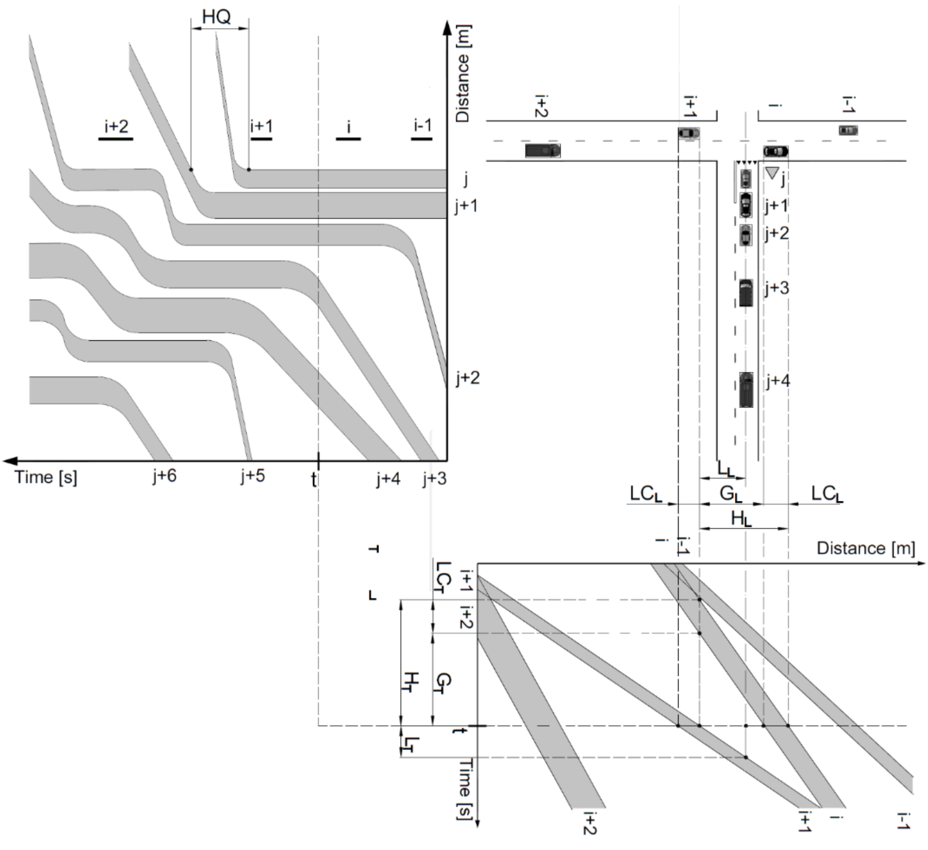

Fig. 4. Spatial and temporal relations in the analysis of traffic at the uncontrolled intersection [own research]

To determine a critical gap, traffic observed at an intersection must meet the conditions resulting from the assumptions of the applied method and the definitions used therein. The research used the method, which was proposed by Siegloch in 1973 to estimate critical gaps and follow-up times for minor streets under saturated conditions. This method requires recording the number of vehicles that can cross or merge the major road if there is a queue at the minor-street approach. It adopts the following assumptions regarding the conditions to be met by the observed traffic (Gerlough & Huber, 1975):

1. The conflict zone at the intersection does not cause delays for the vehicles in the major stream.
2. The major stream is composed only of passenger cars going straight with constant intensity within the entire analysis period.
3. At the major-street approaches, individual vehicles appear independently, randomly, moving in free traffic conditions; there is no grouping of vehicles into columns.
4. Uniform traffic occurs at the entire intersection during the measurement.
5. There are no additional factors at the intersection, such as impedance effect, pedestrian or bicycle traffic, bus stops, or the influence of neighboring traffic lights, which disrupt the entry to the intersection by vehicles from the minor-street approach.
6. Permanent queues of vehicles at the minor-street approaches are created independently for each direction and are composed only of passenger cars.

The Siegloch method maintains strict compliance of the way of estimating the critical gaps with the model for calculating the capacity, based on the gap acceptance theory (Patil & Pawar, 2015). Therefore, it is necessary to know the distribution of the density of time intervals in the major stream as well as the function that connects the number of vehicles crossing or merging the major stream with the length of the gaps, as they are strongly correlated variables. This approach has been further explored in a recent study (Hazim et al., 2019). The Siegloch method requires empirical traffic measurements with a permanent queue of vehicles at the minor-street approach (Chandra et al., 2014). Fig. 5 presents a general flow chart for determining critical gaps and follow-up times according to the method.

The procedure of estimating the critical gap and follow-up time using the Siegloch method is complex and multistage. In practice, estimating the gap acceptance function *g(t)* means recording the number of vehicles entering a major stream in each accepted gap, along with its length (noticed as *t*). After gathering a statistically representative sample of vehicles entering from the subordinate streams in the initial conditions defined according to the assumptions of the Siegloch method, the values corresponding to the behavior of the population of drivers are obtained. The lengths of the rejected and accepted gaps together with the number of vehicles that use them (noticed as *n*) should be separately determined for each minor traffic movement. Independently of the numbers of vehicles entering, the average values of the lengths of the gaps for the set of accepted gaps are calculated.

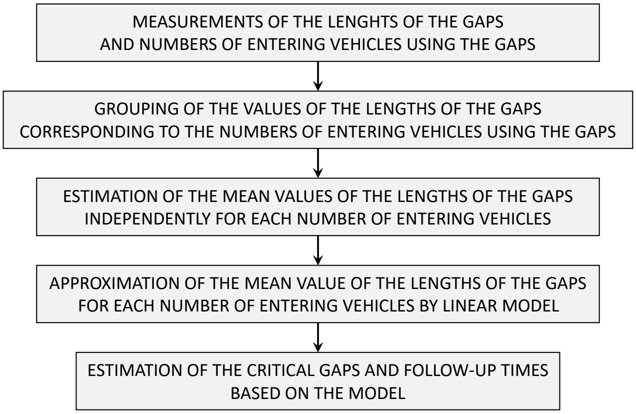

Fig. 5. The general scheme of the Siegloch method [own research]

The empirical data prepared in this way and the average values determined for them form the basis for the building of a linear regression model. It is generally adopted in the Siegloch method that the values of the independent variable are plotted on the ordinate axis. In the gap acceptance model, the number of vehicles entering traffic is such a variable. In turn, the lengths of individual gaps are plotted in the abscissa. An approximation line is needed on the graph for the values of the average length of the gaps used by specific numbers of vehicles. Fig. 6 presents the regression line both in the form of a graph proposed by Siegloch and in a form typical for regression models. These charts are equivalent.
The use of a linear regression model for average values of the lengths of gaps used by 0, 1, 2 up to n vehicles, respectively, crossing or merging the major stream allows to obtain an approximation equation, and consequently also critical gaps as well as follow-up times, where n should be understood as the number of vehicles in each minor movement that have used the same gap G_T in the major stream to merge or cross the traffic. The results of empirical research show that the linear model determined in this way indicates only slight deviations from the average lengths of gaps for individual numbers of vehicles. The values of critical gaps, as well as follow-up times, are estimated directly from the model (Ashalatha & Chandra, 2011; Gaca et al., 2011):

$$\hat{t}(n) = t_0 + t_f \cdot n \tag{1}$$

Where:
$\hat{t}(n)$ – the length of the gap accepted by n vehicles, calculated from the linear model; [s],
t_f – follow-up time; [s],
N – number of vehicles accepting the gap; [PCU],
t_0 – minimum acceptable headway; [s]; the intercept in the horizontal coordinate of headway determined as:

$$t_0 = t_c - \frac{t_f}{2} \tag{2}$$

where:
t_c – critical gap; [s].
The values of critical gaps and follow-up times are determined using the least-squares method and applied to the entire population of drivers. However, the actual value of the individual critical gap is always between the length of rejected and accepted gaps. Depending on the scope of the research, the critical gaps and follow-up times can characterize a real object or a specific type of intersection (Abhishek et al., 2019).
The function of gap acceptance proposed by Siegloch can be written in the following form (Gaca et al., 2011):

$$g(t) = \begin{cases} 0, & \text{for } t < t_0 \\ \frac{t-t_0}{t_f}, & \text{for } t \geq t_0 \end{cases} \tag{3}$$

The function $g(t)$ is understood as the number of vehicles entering the intersection when headways of vehicles on the major-street approach are equal to t. When $g(t)$ is a piecewise function then the following formula may be used (Wu, 2001):

$$g(t) = \sum_{n=0}^{\infty} n \cdot \begin{cases} 1, & t_c + (n-1) \cdot t_f \leq t \leq t_c + n \cdot t_f \\ 0, & \text{other } t \end{cases} \tag{4}$$

The results of the research presented in the literature showed a high level of compliance of the linear approximation function with the step function of gap acceptance applied by many other researchers, such as Tanner, Harders, and Troutbeck (Weinert, 2000). Although some authors consider this method deterministic because it directly uses all data on accepted gaps, it is a stochastic method, due to the probabilistic description of the nature of critical gaps (Brilon et al., 1999).
The Siegloch method is easy to apply in practice and gives both critical gap values and follow-up times. The resulting length of the gap is estimated as an average value determined for the entry of a fixed number of minor street vehicles. However, simulation studies have shown a significant impact of the distribution of headways on the major road on the results obtained (Gaca et al., 2011; AASHTO, 2018).
In addition, the use of this method is limited to saturated conditions, which in practice may not occur on some objects. In such cases, if there are no permanent queues of vehicles on the minor-street approach, estimation of the acceptance function parameters is only possible indirectly, i.e., in an approximate way. Then, the analysis is reduced to observing selected rejected and accepted gaps. In such a situation, it is necessary to use a different method (Wu, 2001).

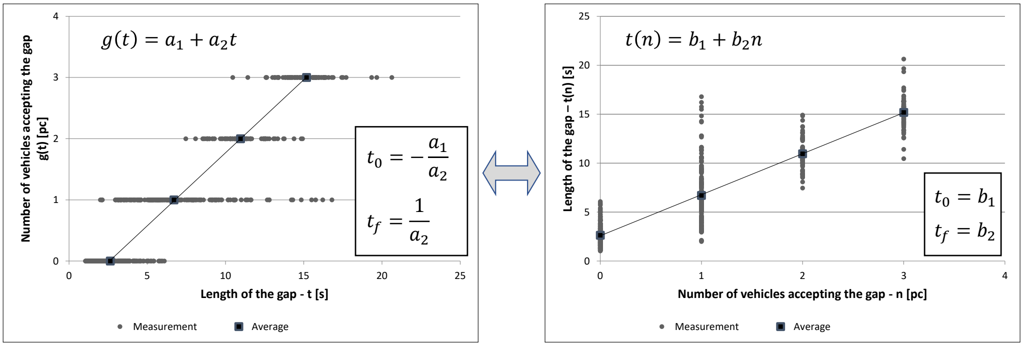

Fig. 6. Graphic presentation of the measurement data and estimated average values in the Siegloch method [own research]

3.2. Formal description of the method

The Siegloch method assumes the construction of separate models for the individual minor traffic movement at the intersection. Therefore, the data on the gaps collected during the measurements have been arranged into subsets referring to individual movements $r \in \boldsymbol{R}$, where the set $\boldsymbol{R}$ includes minor traffic movements. For the MUT-intersection, the set $\boldsymbol{R}$ is determined as:

$$\boldsymbol{R} = \{\mathrm{BL}, \mathrm{CR}, \mathrm{CL1}, \mathrm{CL2}\} \quad (5)$$

Each of the subsets containing the numbers of consecutively registered gaps for individual movement r is described as a vector:

$$\mathbf{V}^r = \langle v_i^r: \quad i = 1, \dots, i^r \rangle, \quad r \in \boldsymbol{R} \quad (6)$$

Where:
i^r – is the number of gaps registered for r-th minor traffic movement.
Every registered gap with the number v_i^r has two parameters:

– $t(v_i^r)$ – the length of the gap v_i^r expressed in [s],
– $n(v_i^r)$ – the number of vehicles in a given minor traffic movement $r \in \boldsymbol{R}$ that cross or merge the major stream during the gap v_i^r.

Thus, for r-th minor traffic movement the following vectors have been described:

$$\mathbf{T}^r = \langle t(v_i^r): \quad v_i^r \in \mathbf{V}^r \rangle, \quad r \in \boldsymbol{R} \quad (7)$$
$$\mathbf{N}^r = \langle n(v_i^r): \quad v_i^r \in \mathbf{V}^r \rangle, \quad r \in \boldsymbol{R} \quad (8)$$

For each minor traffic movement r, it is necessary to determine the maximum number of vehicles crossing or merging the traffic registered during measurements at the intersection, i.e.:

$$n_{\max}^r = \max_i n(v_i^r), \quad i = 1, \dots, i^r, n(v_i^r) \in \mathbf{N}^r, v_i^r \in \mathbf{V}^r, r \in \boldsymbol{R} \quad (9)$$

For further analysis, it is convenient to distinguish another vector $\mathbf{J}^r$, which contains the successive natural numbers for each minor traffic movement $r \in \boldsymbol{R}$, i.e.:

$$\mathbf{J}^r = \langle 0, \cdots, j, \cdots, n_{\max}^r \rangle, \quad r \in \boldsymbol{R} \quad (10)$$

Consequently, the vector $\mathbf{T}^r$ can be divided into $n_{\max}^r + 1$ vectors $\mathbf{T}_j^r$, separated for each minor traffic movement $r \in \boldsymbol{R}$, containing the lengths of the gaps v_i^r accepted by j drivers in the r-th movement, i.e.:

$$\mathbf{T}_j^r = \langle t(v_i^r): \ n(v_i^r) = j, v_i^r \in \mathbf{V}^r \rangle, \ j \in \mathbf{J}^r, r \in \boldsymbol{R} \quad (11)$$

Thus, the measurement results are arranged in such a way that to each gap with the number v_i^r has been assigned both its length $t(v_i^r)$ and the number of vehicles crossing or merging the traffic - $n(v_i^r)$. Such data arrangement facilitates the calculation of the critical gaps and follow-up times independently for each movement $r \in \boldsymbol{R}$.
The average length of the gaps accepted by a given j-th number of drivers for each minor traffic movement $r \in \boldsymbol{R}$, is calculated according to the formula:

$$t_{\mathrm{avg},j}^r = \frac{\sum_{\mathbf{T}_j^r} t(v_i^r)}{|\mathbf{T}_j^r|}, \quad j \in \mathbf{J}^r, r \in \boldsymbol{R} \quad (12)$$

where $|\mathbf{T}_j^r|$ is the number of elements in the vector $\mathbf{T}_j^r$. The average lengths of the gaps $t_{\text{avg},j}^r$ are the points on the graph for which, the least-squares method is used to calculate a linear approximation of the relationship between the number of vehicles crossing or merging the major stream and the average length of the gaps accepted by the drivers.
The set of values of the average length of gaps $t_{\text{avg},j}^r$ for each minor traffic movement $r \in \boldsymbol{R}$ may be presented in the form of the following vector:

$$\mathbf{T}_{\text{avg}}^r = \langle t_{\text{avg},j}^r: \quad j \in \mathbf{J}^r \rangle, \qquad r \in \boldsymbol{R} \tag{13}$$

To apply the Gauss approximation formulas, it is necessary to determine for each minor movement:

– the average length of all gaps registered, i.e.:

$$t_{\text{avg}}^r = \frac{\sum_{j \in \mathbf{J}^r} t_{\text{avg},j}^r}{n_{\max}^r + 1}, \qquad r \in \boldsymbol{R} \tag{14}$$

– the average number of vehicles crossing or merging the traffic, that is:

$$j_{\text{avg}}^r = \frac{\sum_{j \in \mathbf{J}^r} j}{n_{\max}^r + 1}, \qquad r \in \boldsymbol{R} \tag{15}$$

The next step in the process of building a linear regression model is to determine the values of the line coefficients that approximate the relationship between the number of vehicles that cross or merge the traffic in a gap and the average length of the gaps they accept. These coefficients are also presented in Fig. 6. The slope is determined according to the formula:

$$b_2^r = \frac{\sum_{j \in \mathbf{J}^r} \left(j - j_{\text{avg}}^r\right)\left(t_{\text{avg},j}^r - t_{\text{avg}}^r\right)}{\sum_{\in \mathbf{J}^r} \left(j - j_{\text{avg}}^r\right)^2}, \qquad r \in \boldsymbol{R} \tag{16}$$

The y-intercept is determined according to the formula:

$$b_1^r = t_{\text{avg}}^r - b_2^r \cdot j_{\text{avg}}^r, \qquad r \in \boldsymbol{R} \tag{17}$$

The values for the critical gaps and the follow-up times for each movement are closely related to the values of the determined coefficients of the approximation. The follow-up times are equal to the slopes, that is:

$$t_f^r = b_2^r, \qquad r \in \boldsymbol{R} \tag{18}$$

In turn, the critical gaps are functions of the values of both determined coefficients of the approximating line, i.e.:

$$t_c^r = b_1^r + \frac{b_2^r}{2}, \qquad r \in \boldsymbol{R} \tag{19}$$

The presented formal description concerns the MUT-intersection, however, the procedure of estimation of the critical gaps and follow-up times according to the Siegloch method can be used for any type of uncontrolled intersection, regardless of the number and type of movements present at the object, its geometry, and the scope of the research, which may cover both the entire intersection and only a selected minor traffic movement. The changes would then only apply to the set of analyzed movements $\boldsymbol{R}$.

4. Case study

Based on the theoretical analysis and pilot studies carried out by the authors, the set of experiences, comments, and observations has been collected, which allowed, after conducting basic research and using the Siegloch method, to determine the critical gaps and follow-up times for the minor traffic movements on the real object.
The research intersection is in the built-up area in one of the central districts of the city of Katowice in Poland (Fig. 7). It is in the area serving commercial and service functions. The major street constitutes the connection between the northern and southern districts of the city and their connection to the downtown. It has a longitudinal route between the A4 and Drogowa Trasa Średnicowa motorways, which additionally emphasizes its importance not only locally, within, or between districts, but also on the scale of the entire agglomeration, ensuring the connection with neighboring cities such as Chorzów, Mikołów and Ruda Śląska. The object handles internal as well as external source and destination traffic. The dominant traffic stream is on the major road in the longitudinal direction, i.e. A-B (Fig. 7).
The values of critical gaps and follow-up times were determined for the four minor traffic movements. Fig. 8 shows the scheme of the intersection under study and the marking out of the virtual measurement sections visible from the adopted vantage point, where a camera recording the traffic situation was placed.

The research was conducted in spring 2018, on Wednesdays and Thursdays in sunny weather. The exact hours and days were chosen based on the experience of the authors, knowledge of the area, and information on average traffic volumes and their fluctuations. The observation of the entire area of the intersection was carried out with the use of a camera located at a height of about 6 meters above the road level on the viaduct near the object. Virtual cross-sections (Fig. 8) perpendicularly to the road axis were marked out. They were established in space by basing them on the physical elements present at the intersection. The collected footage covering 16 h (four measurement days) was analyzed. All traffic situations that meet the assumptions of the Siegloch method were used for the analysis. Due to the research conducted during the afternoon rush and the uniform traffic on all approaches to neighbor intersections, no significant temporary fluctuations in the traffic intensity on the major road were observed. In the vast majority of cases, the critical gaps are determined in real traffic conditions, which makes it impossible to isolate the intersection from the influence of the surroundings (Gerlough & Huber, 1975; Thamizh & Reebu, 2005; Nabaee, 2011; Ramu et al., 2015; Abhignai et al., 2016; Chodur & Bąk, 2016; Dutta & Ahmed, 2017; Shaaban & Hamad, 2017; Rao & Gaddam, 2019; Witt et al., 2019; Zacharia et al., 2019).

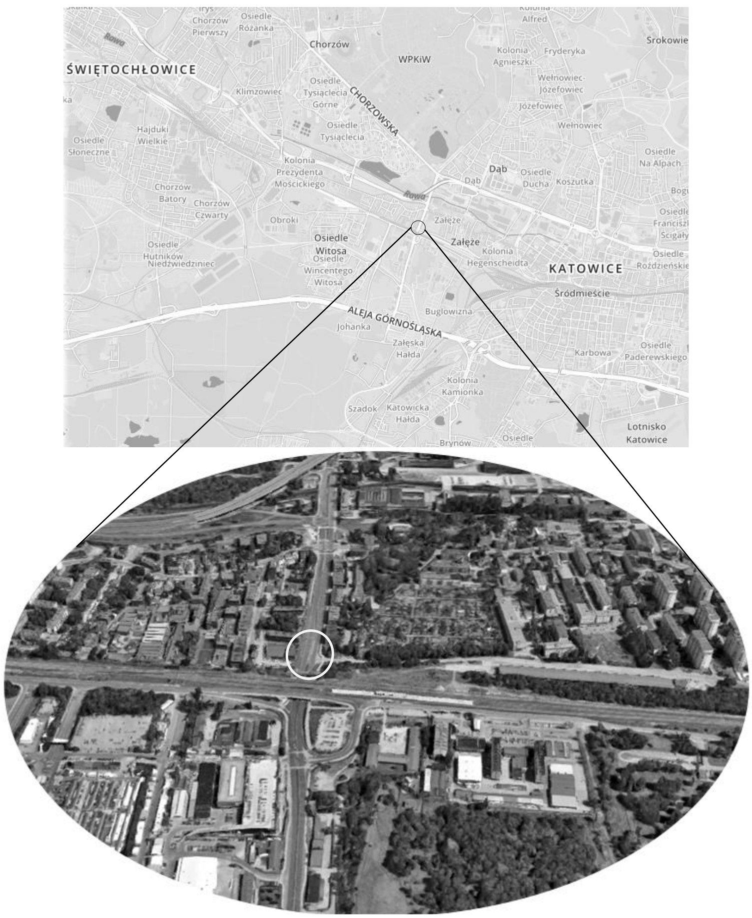

Fig. 7. Location of the intersection within the transportation system of the city of Katowice city [own research based on (© OpenStreetMap, 2020)]

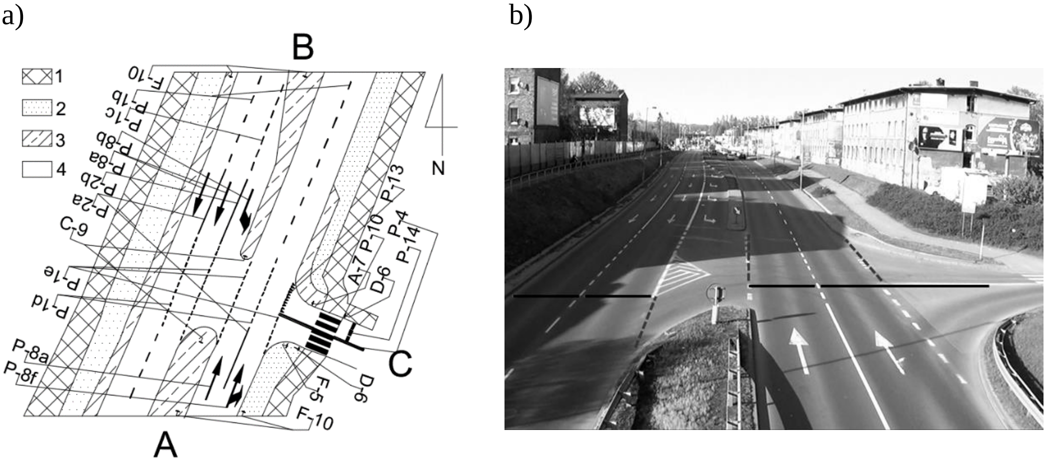

Fig. 8. The intersection under study: a) the scheme of the intersection (designation of the surface type: 1 – sidewalk, 2 - grass, 3 - pavement, 4 - road); b) the view from the vantage point with marked virtual measurement sections (solid line - major traffic flows, dashed line - minor traffic flows) [own research]

Table 1 contains selected measures of descriptive statistics that characterize the structure of the data, that is, a set of recorded road situations separately for each number of vehicles crossing or merging the major stream for each minor traffic movement. To assess the representativeness and size of the sample, the mathematical apparatus presented in (Zeliaś et al., 2002) has been used. The analysis of the behavior of individual drivers waiting for the possibility to continue driving was conducted separately for each minor traffic movement (similarly to the entire subsequent analysis). Each time, the length of the gap and the number of vehicles using it were noted. This allowed determining the values of the critical gaps presented in Table 1.

Fig. 9. shows the results of the analysis of the obtained sample. For all movements, a moderate right-hand asymmetry of the distribution is visible. The length of accepted gaps mainly ranges from 4 to 10 s. The effect of a median on facilitating the merging vehicles in the second stage of left-turn movement from the minor-street approach is also apparent.

For the left turn from the major-street approach, the distribution of the number of accepted gaps as a function of their length is more concentrated than for the right turn movement from the minor-street approach. This is due to the different number of lanes at the exit of the intersection (Chodur & Bąk, 2016). In Table 2 the results of the research have been presented and compared with the values contained in the Polish manual.

The smallest value of the critical gap occurs for the movement CL2 and the largest - for CL1, which is directly related to the median accommodating one vehicle and shows its impact on the capacity and traffic conditions. The second very important factor determining the critical gap for these movements is the presence of two major two-lane roadways on the major-street approach, which causes the distribution of the first-order stream into two traffic lanes. This is reflected in the lengths of the critical gap assigned to the CL2 and CR movements that are smaller than the corresponding values recommended by the Polish manual. Additionally, the indirect impact of an additional factor on the critical gaps was captured here for the CR movement. The flared-lane approach allows for the creation of independent queues of vehicles, which is particularly important when the measurements are carried out in real traffic conditions, but it limits for drivers in the CR movement the possibility of observing the major traffic movement due to the presence of the parallel queue of vehicles turning left from the minor-street approach. Minor traffic movements (BL, CL1) are related to the same higher-ranked traffic movements; the difference between the designated critical gaps results from the various behavior of drivers and their possibilities of continuing driving after the maneuver.

The research results presented in Table 2 show that the considered type of intersection is different from the objects located on roads of type 1x2. In the Polish manual, there are no values of critical gaps and follow-up times consistent with the movement priority, and the way of interaction of individual streams that occur at MUT-intersections. The lack of good estimates of the values of critical gaps and follow-up times does not allow for a precise calculation of the capacity and assessment of traffic conditions on such objects. The Polish manual recommends taking the values determined for 1x2 road intersections and such data have been included in Table 2. To compare the values in the corresponding movements, for the Polish method, the values of critical gaps and follow-up times relating to the straight traffic movement from the minor-street approach were adopted. In turn, the movement marked as CL2 relates to the critical gap and the follow-up time for the left-turn movement from the minor-street approach (Brilon, 2009; Patil & Sangole, 2015; Pawar et al., 2015; Tanackov et al., 2018; Abhignai et al., 2020).

The values of follow-up times determined for each of the four studied movements are greater than those recommended in the manual and more similar, but also greater than the value of the critical gap for the corresponding movements. This indicates the caution of drivers and emphasizes the existence of completely different tendencies than at 1x2 road intersections, where, based on the data in Table 2 for the Polish method, the inverse relationship between the values of critical gaps and follow-up times in individual movements may be observed. In the that a group of vehicles enters from the minor-street approach in one gap, each driver independently assesses the possibility of crossing or merging the traffic.

Table 1. Characteristics of the research sample constituting the basis for the analysis [own research]

Descriptive statistics of the length of the gap	**Number of vehicles (*j*) crossing or merging the major stream**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Minor traffic movement: left turn from the major road (BL)									
Mean value - $t_{\text{avg},j}^{\text{BL}}$ [s]	1.4	6.4	9.5	13.0					
Variance [s^2]	0.4	3.9	3.2	1.6					
Coefficient of variation CV [-]	0.4	0.3	0.2	0.1					
Required sample size [-]	10	104	84	43					
Obtained sample size [-]	174	131	92	53					
Minor traffic movement: right turn from the minor road (CR)									
Mean value - $t_{\text{avg},j}^{\text{CR}}$ [s]	2.6	6.7	11.0	15.2					
Variance [s^2]	1.4	7.0	2.6	2.7					
Coefficient of variation CV [-]	0.4	0.4	0.1	0.1					
Required sample size [-]	37	187	70	73					
Obtained sample size [-]	227	245	78	79					
Minor traffic movement: left turn from the minor road – I stage (CL1)									
Mean value - $t_{\text{avg},j}^{\text{CL1}}$ [s]	2.6	8.1	13.8	18.2	25.4	29.9	30.4		
Variance [s^2]	2.3	15.0	11.3	7.5	4.8	3.4	0.8		
Coefficient of variation CV [-]	0.6	0.5	0.2	0.1	0.1	0.1	0.0		
Required sample size [-]	61	398	299	199	129	92	23		
Obtained sample size [-]	789	416	308	213	131	95	31		
Minor traffic movement: left turn from the minor road – II stage (CL2)									
Mean value - $t_{\text{avg},j}^{\text{CL2}}$ [s]	2.1	5.2	8.3	10.5	12.4	19.3	21.1	28.9	32.6
Variance [s^2]	2.2	2.8	4.3	5.0	3.4	4.9	3.9	3.0	0.6
Coefficient of variation CV [-]	0.7	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0
Required sample size [-]	60	73	115	133	91	132	103	81	18
Obtained sample size [-]	450	466	233	159	106	133	104	82	23

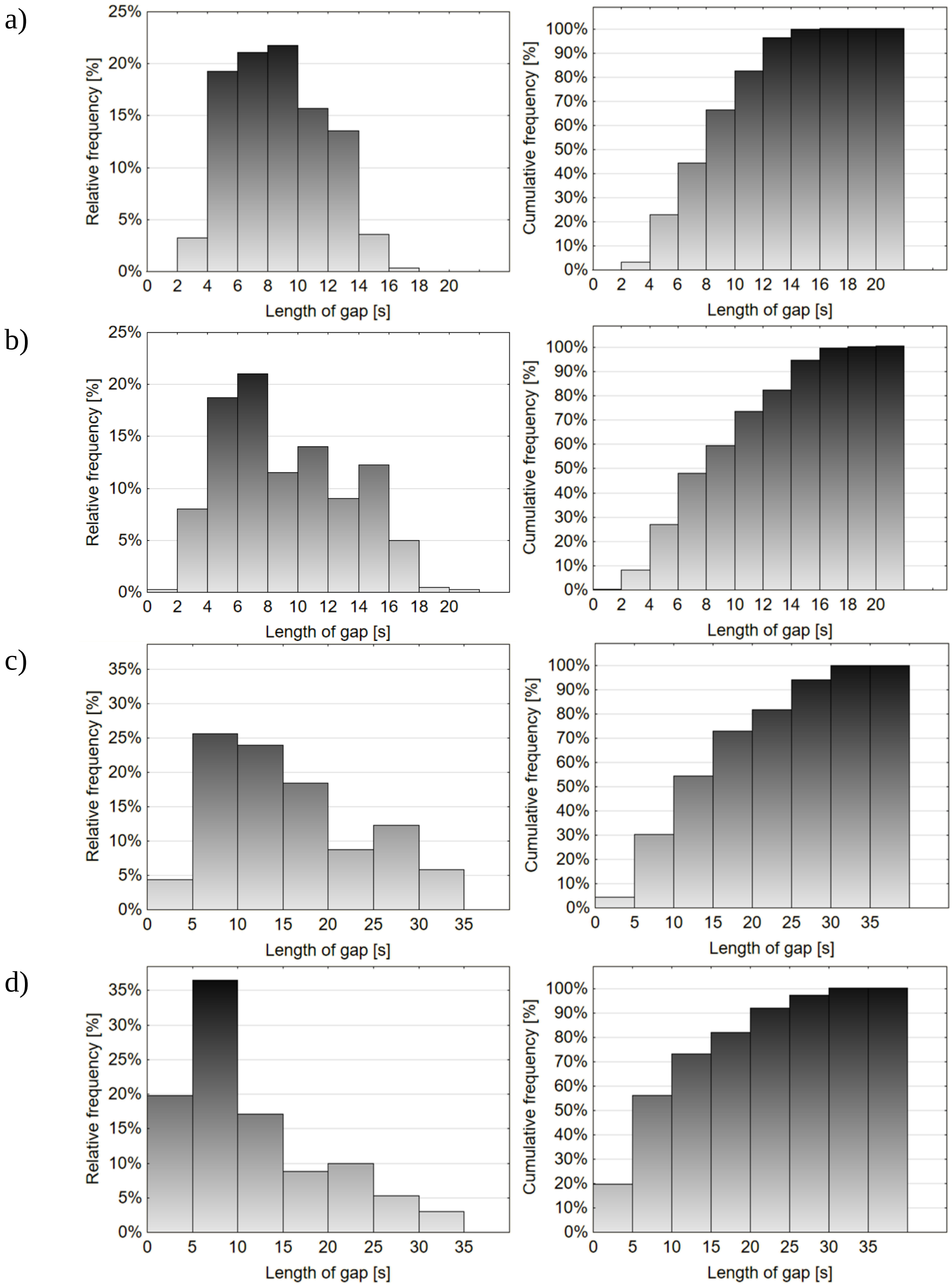

Fig. 9. Relative and cumulative frequency distribution of the length of gaps for the minor traffic movements, a) left turn from the major-street approach (BL); b) right turn from the minor-street approach (CR); c) left turn from the minor-street approach – I stage (CL1); d) left turn from the minor-street approach– II stage (CL2) [own research]

Table 2. Values of critical gaps and follow-up times [s] for the minor traffic movements [own research based on (GDDKiA, 2004)]

Parameter	Research results				Polish manual			
	BL	CP	CL1	CL2	BL	CP	CL1	CL2
Critical gap – t_c^r	3.7	4.6	5.88	2.3	5.7	5.4	5.5	5.6
Follow-up time – t_f^r	3.7	4.1	4.97	3.7	2.5	3.1	3.3	3.2

The smallest discrepancy between the empirical values for a given intersection and those recommended in the Polish manual is for the CL2 movement. This results from the ways of creating a queue and the entry of subsequent vehicles from the minor-street approach. On the other hand, the greatest discrepancy in this respect occurs for the CL1 movement, because on the MUT-intersection crossing the conflict zone in groups is very difficult for drivers performing this movement due to median. It can refuge only one vehicle, while subsequent drivers must wait for this area to be freed up to continue driving. The captured tendencies in the differentiation of the values of follow-up times at both stages of a left turn compared to the values recommended in the manual confirm that this element of the geometry and organization of traffic at intersections of the type is the most characteristic. For the right turn movement from the minor-street approach, the differentiation of the values of the follow-up times results from the reduced visibility.

Summarizing the results presented, it should be noted that each time the values of the critical gaps and follow-up times are different from the recommended ones in the Polish manual. This may be related primarily to the different geometry of the intersection, as well as the worse traffic organization at the intersection, at which the drivers wait in the queue. The measurements showed the different nature of the analyzed uncontrolled median T-intersection in comparison to the objects at the crossing of roads of 1x2 type. Due to the described significant influence of the intersection geometry on the values of the critical gaps and follow-up times, it seems reasonable to use them to calibrate the models of estimation the capacity of objects

5. Discussion

The presence of a median at an intersection means that the left turn movement from a minor-street approach is realized in two stages and therefore it can be considered as two separate movements, i.e., CL1 and CL2. This is the most specific element of a given type of intersection, causing different interactions between vehicles than in the case of a typical four-leg intersection (HBS, 2001; GDDKiA, 2004; TRB, 2010; Gaca et al., 2011; AASHTO, 2018). Crossing the major road, which is the first part of the left-turn movement (CL1), in practice corresponds to the through movement at a 1x2 road intersection, with only one priority stream using two lanes. Also, adopting the values of critical gaps and of follow-up times recommended in the Polish manual for left-turn movements from the minor-street approach during the second stage of turning may differ from the actual values.

The Polish manual includes a separate procedure for estimating the capacity of four-leg median uncontrolled intersections, adopting a two-stage model of crossing the major road, and the resulting modification of the method of determining the conflicting flow rate and capacity of the minor traffic movement. The estimation procedure for four-leg median intersection is allowed also for MUT-intersection, but the different influence of major traffic movements in the subordinate streams is not taken into account. Thus, this method requires adjusting and adapting the procedures to the specific conditions of MUT-intersections.

The article aimed to determine the critical gaps and follow-up times based on traffic observations at local intersections so that they can constitute a calibration tool for the capacity estimation method. The obtained values of critical gaps and follow-up times are specific for the selected object; however, to estimate universal values representing a whole set of intersections belonging to a given type (i.e., MUT-intersection), a further in-depth research is necessary. For all minor traffic movements, the estimated values of the critical gaps are smaller than those recommended in the Polish manual, which may lead to the hypothesis that the MUT-intersection allows the traffic in individual movements much more efficiently than 1x2 road crossings.

Due to the lack of precise, adapted, and calibrated calculation procedures for MUT-intersections that would allow estimating the capacity, nowadays it is impossible to provide a reliable assessment of the traffic conditions using analytical methods. This is mainly due to the lack of guidelines to determine the conflicting flow rate, which is used in many stages of the calculation procedure and is one of the basic parameters of the model. The more steps of the method will be performed, the greater the error resulting from the inaccuracy of parameters acceptance.

To assess, at least in an indicative way, the impact of the critical gaps and follow-up times estimated according to the Sigloch method presented in the article on traffic conditions, the values of the potential capacity estimated based on critical gaps and follow-up times adopted from the Polish manual and the values determined by the authors have been compared. The results of the analysis are presented in Fig. 10.

The results obtained confirm previous observations that the presence of a median, major two-lane roadways, and a smaller number of influencing streams improve traffic conditions in respect to 1x2 intersections. For all movements examined for large values of the assumed conflicting flow rate, the values of the potential capacity determined based on the results obtained are higher than in the case of the application of the critical gaps and follow-up times recommended in the Polish manual.

Comparing the shapes of the curves in both graphs in Fig. 10, i.e., a) and b), in the case of the results based on the Siegloch method, less rapid nature of the decrease in the capacity for minor traffic movement with the increase of the conflicting flow rate was noticed than in the case of the graphs prepared according to the Polish manual.

The beneficial effect of the median and major two-lane roadways on the capacity of the CL2 movement is visible. In the whole range of the conflicting flow rate examined, the estimated value of the potential capacity is very large and undergoes little change. The BL movement also assumes higher potential capacity values than indicated in the Polish manual. The reason for this is that there are no impedance effects and only one minor-street approach.

For the remaining minor traffic movements analyzed, the obtained shape of the potential capacity function is similar to the Polish manual. As expected, the CL1 movement takes the lowest values of the potential capacity among all the examined movements, resulting from the impedance and the dependence on the number of vehicles in the median.

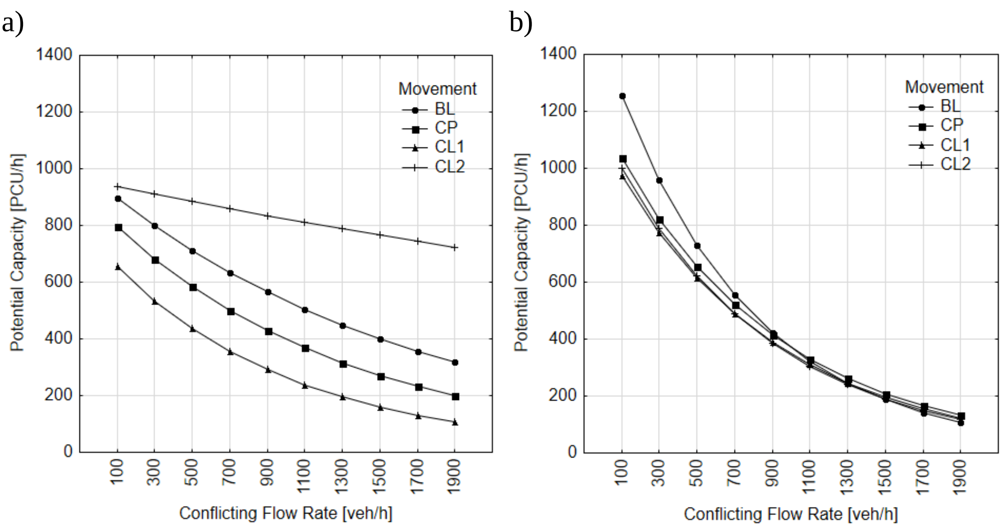

Fig. 10. Potential capacity for all minor traffic movements as a function of conflicting flow rate for local intersection based on different t_c and t_f values: a) t_c and t_f values experimentally determined; b) t_c and t_f values adopted from the Polish manual [own research]

The application of the procedures recommended in the Polish manual causes that, in the range of the conflicting flow rate below 300 veh/h, the estimated potential capacity assumes higher values than it is for the empirically determined values of the critical gaps and follow-up times. However, for values above 300 veh/h, the estimated value of the potential capacity decreases significantly. Therefore, the values indicated in the Polish manual should be used with great care to estimate the capacity of MUT intersections.
The results for the selected object are specific and different from those in other types of intersections. Each object of the tested type handles different traffic, and the drivers who use it behave differently. To determine the values of critical gaps and follow-up times that characterize a given type of intersection, it would be necessary to define much more stringent conditions that must be met. Only the values of accepted and rejected gaps registered in traffic conditions consistent for all objects should be assumed for the model (Nabaee, 2011, Rao & Gaddam, 2019). Thus, it is necessary to extend the scope of research to other objects of a given type.
The primary purpose of estimating capacity is to assess traffic conditions. The capacity is directly and indirectly influenced by many factors, including the critical gaps and follow-up times examined in this article. Prioritizing individual factors and assessing the statistical significance of their impact should constitute a further research direction within a broad area of activities. It is necessary to perform an analysis of capacity sensitivity as a function of critical gaps and follow-up times.
An extensive issue may be the identification of factors that influence the critical gaps and the follow-up times for each minor traffic movement and the determination of the strength of this impact. A related research area, necessary for further analysis, is the assessment of the behavior and risk propensity of drivers on the examined type of intersection. It is noteworthy that the proposed approach may be applied to the characteristics of other uncontrolled intersections with niche geometric solutions.
The article aimed to analyze the process of estimating the critical gaps and follow-up times according to the Siegloch method. The practical activities undertaken by the authors were conducted in the form of pilot studies. It was verified and, as a result, the validity of the development of an individual approach to the estimation of the values of critical gaps and follow-up times at MUT-intersections with rare geometric conditions and traffic organization was confirmed. This article is intended to start a scientific discussion in the field of estimating the critical gaps and follow-up times in this type of object and to indicate the directions of actions necessary to be taken in the future. Therefore, the presented results of the research should be treated as preliminary characteristics in this regard.
The subject of the analysis was MUT-intersections in terms of estimating the values of critical gaps and follow-up times for the minor traffic movements. This problem is more important and current, as the capacity of individual infrastructure facilities determines the efficiency of the entire transportation system and affects the travel time and comfort of its users. Capacity and assessment of traffic conditions are the basis for spatial planning of the entire road transportation system. Precise estimation of them is possible only when the exact values of the factors that determine them are known, including the values of the critical gaps and follow-up times, presented in the article.

6. Conclusions

The idea of the article is to determine the critical gaps and follow-up times based on the observation of traffic at individual MUT-intersection so that they constitute a calibration tool for the method of estimating capacity. The analysis has indicated that the objects of the type analyzed are not well studied in the literature. The features of the examined objects distinguish them from other uncontrolled intersections. Therefore, it requires a specific approach to the estimation of critical gaps and follow-up times. The analysis of the stream hierarchy, traffic organization, and geometry conditions confirmed that the theoretical methods of estimating the capacity used in the HCM, HBS, and Polish manual do not allow the assessment of traffic conditions at intersections of the examined type.

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