WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2025.153348
ARCHIVES OF CIVIL ENGINEERING
Vol. LXXI ISSUE 1 2025

pp. 523 – 541

Research paper

Dilemmas of intersection queue length estimation in traffic capacity analyses

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Abstract: Residual queues are one of fundamental traffic quantities indicating the traffic performance of signalized road intersections. Intersection queues indicate traffic congestion, i.e., traffic jams building up on the road system. Accurate queue length estimation is an essential part of road intersection and system performance assessments and the associated decision-making process. This is particularly important in the geometric design of intersections and in arterial congestion analyses. The analyses and comparisons presented in this article relate mainly to the new Polish guidelines for performing road traffic measurements (WR-D-12). Alternative ways of estimating queues were also checked in terms of their estimation accuracy. The first part of article gives a review of the literature on the traffic queue estimation methods. Then, own research results were characterized to show the complexity of the issue of residual queues at signalized intersections. Further on, different vehicle queue estimation approaches are analyzed, including the guidance provided in WR-D-12. A comparative analysis of empirical data obtained on a few intersections was conducted at this point of our study. The final part of this article includes the authors' conclusions and recommendations for correct estimation and accurate determination of residual vehicles number for traffic capacity analyses.

Keywords: vehicle queues, traffic lights, traffic surveys

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1. Introduction

Road surveys are the key component of traffic data for traffic engineers. This information is used to support urban planning decisions, considering the mobility requirements for private and public means of transport. The survey results are also used in analyses conducted to support the choice of appropriate engineering options during the road infrastructure design process. These engineering options include road cross-section, the number of traffic lanes, road connections and crossing types including vehicle accumulation zones, i.e., intersection or interchange areas. Furthermore, the survey results are also used for performance evaluation of the existing road systems in urban or rural areas from the traffic capacity or traffic safety point of view. The above-mentioned data are also used in real-time traffic signal control systems. Without this kind of knowledge on current or forecasted transport demand in hand it would be ineffective or unreasonable to undertake any road planning, engineering, or maintenance activities. The potential errors may include excessive spending due to over-designed road infrastructure construction/alteration projects on the one hand or underrated traffic capacity demand leading to excessive trip delay, far-reaching vehicle queues with the resulting increase in air pollution, or increased driver stress with potential traffic safety impacts [1–5].

In 2022 a major change in road infrastructure engineering took place in Poland, in which traffic safety issues played a significant role [6]. The previous public road engineering and location requirements were superseded by the provisions of the new public road construction code [7]. The underlying idea was to change the order of precedence and responsibility of road design engineers in relation to the choice of infrastructure design options. The code provisions that constitute the canon of knowledge on the available land transport infrastructure engineering have been completely reworded and 'stripped' of the substantial amount of data previously specified in relation to specific engineering details. Most of these strictly technical issues have been moved to WR-D's road engineering manuals. These are dedicated brochures containing the most current technical knowledge recommended for practical application by the Polish minister for transport. Nevertheless, the construction code provisions must be applied as an obligatory requirement [7]. Thus, they should be treated as the backbone of road infrastructure design. In turn, all the recommended standard designs and their allowable departures are described in the above-mentioned WR-D's manuals. Note that the knowledge contained in WR-D's manuals is intended for optional application and may or may not be used by the road engineers. Hence the designer may as well apply the technical knowledge provided in another source of technical knowledge or rely on his or her licensed senior engineer's experience in the field.

One of these WR-D's manuals, the WR-D-12 called *Road traffic survey guidelines* [8], has been reviewed as part of this study. It was recommended for application on 2 December 2022 (rev. 01). It provides an exceptionally reliable presentation of traffic surveys on urban streets and rural roads and highways. One of its subsections deals with intersection queue measurements, primarily for signalized intersections. The analyzes of WR-D-12 focused on the problem of measuring vehicle queues.

These topics are, in Authors opinion, covered too generally, missing more in-depth knowledge on the queue building up process, investigation and potential use of the queue tail length data in engineering practice. Therefore, it is justified to assume insufficient accuracy of the proposed residual queue survey method for road traffic analyses, especially during peak hours in residential parts of large urban areas. In addition, the residual vehicles counting method proposed in the above-mentioned guidelines appeared questionable to us. Our concern was that in this method the residual vehicles numbers are measured over short (5-minute) time-spans and then a mean of three subsequent intervals is calculated for a 15-minute period. Thus, we decided to verify, as part of this study, the reliability and accuracy of the residual vehicles counting method proposed in [8]. For this purpose, we used the results of our own queue length and back-of-queue size data from the surveys carried out on signalized intersections [9–13]. The study area chosen for this study was a signalized intersections.

2. Literature review of residual queue surveys

In general, manual or fully automatic methods are used to determine the queue length in the number of vehicles or in distance (further called "tail distance"). In manual techniques, queued vehicles are counted in relation to a given traffic control state, e.g., the end of the green or red phase or to a given time span (e.g., one signal phase, or a time interval of five or fifteen minutes). Surveys of this kind were carried out, for example, as part of the studies reported in [12–17]. In semi-automatic surveys video recording techniques are used. The queue images are taken up to the queue tail, and then analyzed by sight to determine the numbers of queued vehicles and tail lengths. This empirical queue length determination method (both in the number of vehicle and in distance) was applied, for example, in the studies reported in [18–22]. In automatic methods the queue parameters are determined by appropriate algorithms. Tracking of movement paths of objects identified as vehicles on the video track is the most popular automatic method [23–30]. Also popular is traffic detection with inductive loops sited at pre-defined locations along the traffic lanes. This survey method was used, for example, in the studies reported in [31–33]. Yet another survey method uses magnetic sensors sited along a lane, as described for example in [34]. Attempts were also made to parametrise the tail lengths by application of shockwave theory using test vehicles and GPS tracking techniques. These methods were used for example in [35, 36]. On the other hand, quite a number of studies providing input for development of queue length estimation models (in distance or in the number of vehicles, as appropriate) are based on traffic simulations. The studies reported in [37–44] are an example of such simulations. Like it is the case with any theory, these models need to be empirically verified, for which the above-mentioned traffic survey methods may be applied on carefully chosen sites.

The method of determination of the maximum queue length is to this day based on the output of the study published in [45]. Also, the residual queue determination method has remained largely the same as it is still based on the output of the studies presented in [46, 47]. Furthermore, most design guidelines [48–54] are based on the same queue determination concept. For example, in [47] a coordinate transformation method was applied in relation to the steady-state delay curve [55]. This model considered a canon of the queue formation process is based on relationships described, for example, in [46, 47, 55, 56]. The average residual queue length determination model proposed for specific period of analysis [47] was subsequently modified in [46]. As a result, a zero-length residual queue is arbitrarily taken for the traffic loads below the X_{gr} threshold calculated with equation 3a from [46].

The average residual queue length modelling methods found in most if not all contemporary design is generally in agreement with the model proposed in [46]. This model in its final form is still used in the Australian guidelines [48]. It was also recommended for traffic engineering calculations in Poland [57], even before the issue of the official design guidelines [60]. The residual queue models used in other countries differ from the model proposed in [46] by adoption of appropriate adjustment factors to improve accuracy or skipping the zero-length residual queue assumed in the original model [50–54]. A completely different model is used in Canada [49]. It is based directly on a deterministic model considering the difference between the arrival flow volume and the traffic capacity of the intersection in question.

The following conclusions are drawn from the literature review. The problem of correctly measuring the length of queues at signalized intersections is complex. Likewise, the reliable estimation of the value of the length of these queues in engineering issues is challenging. Therefore, the Authors of the publication have tried to perform their own analyses of the accuracy of estimation by means of the proposed methods of testing vehicle queues.

3. Field study carried out as part of this research

In our study we determined the residual queue length by counting the number of vehicles that were not able to pass through the intersection during the green signal phase of a given i-th signaling cycle. This was a set of vehicles coming from the maximum queue of this i-th signaling cycle that have remained queued in the approach leg waiting there for the next, i.e. $i + 1$-th signaling cycle. The principle of determination of the number of vehicles in cycle $i+1$ is schematically represented in Fig. 1.

Two methods were used in this survey. In the first method we counted the vehicles that remained in the intersection approach leg after one signaling cycle. The counting itself was done by trained staff taking part in the field study. The second, semi-automatic method was based on images recorded on video cameras deployed on the street. The cameras were mounted on street lights ca. 5.0 m above ground. The videos recorded on these cameras were combined into a single clip showing the whole section under analysis. Next the clip was examined by an observer who took down the number of vehicles that did not pass through the intersection in one signaling cycle. The details of vehicles approaching and leaving the intersection leg, leaving the queue, and stopping at the queue tail were logged in the process. These methods are described in detail in [58]. No electric vehicle has been reported in the study, demonstrating different dynamic performance relative to conventional vehicle propulsion systems – as highlighted, for example, in the work [59–61].

The surveys in relation to this study were carried out in Bydgoszcz (three intersections), Toruń, Warsaw and Kraków (one intersection each). All of them are located in Poland and differ in terms of land use, number of inhabitants and also social and economic development. Thus, the queue formation process was analyzed on ten different traffic lanes featuring no lateral traffic interference related to parking or non-signalized intersections on the way. There were no green arrow signals on the tested lanes.

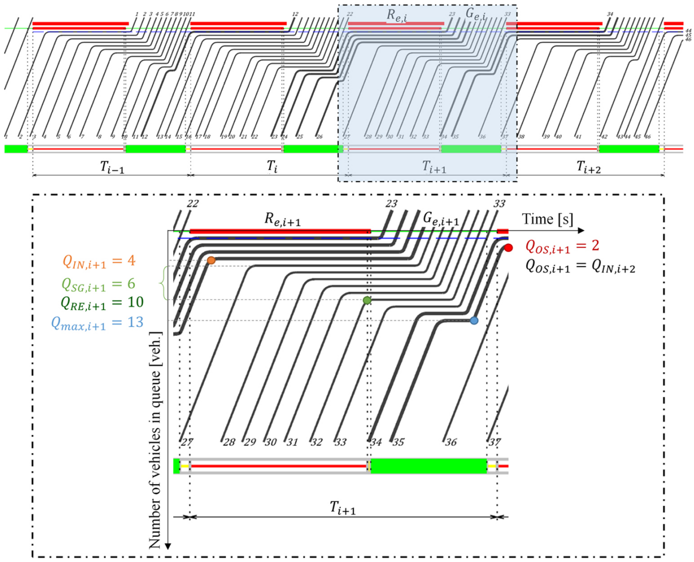

Fig. 1. The process of building up the queue to the maximum length in a given signaling cycle, showing the residual queue length, based on [9]. Variables: I – signaling cycle number, Q_{IN} – initial queue, Q_{SG} – queue of vehicles stopped on the red signal only, Q_{RE} – queue of vehicles stopped due to red effective time, Q_{OS} – residual queue, $Q_{\max}$ – maximum back-of-queue size (maximum queue length in distance), R_e – red effective time, G_e – green effective time, T – signaling cycle time

4. Residual queue formation problems

Hourly volume-to-capacity ratio is the key measure of the intersection performance (calculated as the traffic demand to capacity ratio), relating the arrival flow volume to a group of lanes to their capacity. It can be calculated for a specific traffic lane using the following equation:

$$X = \frac{q}{c}, \ [-] \tag{4.1}$$

where: X – traffic lane volume-to-capacity ratio [–], q – arrival flow volume on a given intersection entry lane [veh./h], c – lane capacity [veh./h].

The volume-to-capacity ratio X is one of the basic input parameters used to estimate delay, queue length and number of stops [1, 3, 4, 48–54]. A high value of X may indicate presence of residual queues of vehicles that could not pass through the intersection during green phase. These queues are designated Q_{OS} and are used as congestion indicators in traffic engineering practice. Depending on the arrival flow volume q and its momentary variations in relation to traffic capacity c, residual queues may build up already at $X \geq 0.7$ [46, 56, 59], which also has been confirmed in our short-term analyses (Fig. 2). It is important to see in this figure the significant impact of short analysis periods and correct estimation of lane capacity in a single signaling cycle on the extent of the remaining queues.

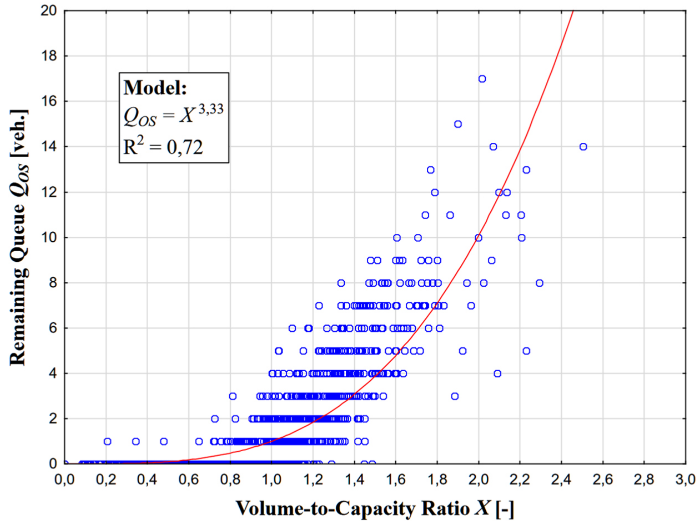

Fig. 2. The observed residual single-cycle queue lengths Q_{OS} vs. the lane volume-to-capacity ratio X (the X value calculated for the analysis period of a single signaling cycle)

A traffic lane is considered congested when residual queues persist in the lane for a few or more signaling cycles [13, 62]. The main cause of singular residual queues build up is the turbulent arrival flow in $X < 1.0$ traffic situations rather than the lane congestion itself (insufficient capacity of the lane due to too short green time) [46, 56, 59]. At such saturation degrees dispersion of platoons heading to the intersection during the green phase may result in some vehicles that mainly travel with excessive space headway failing to pass through the intersection before the signal turns red. Consequently, these vehicles form a residual queue consisting of logged vehicles identified in the arrival flow, which failed to enter the departure flow of a given signaling cycle.

When the lane arrival volume exceeds the capacity for longer time periods, the traffic quantities, including the residual queue lengths become a function of congestion time until the X value has sufficiently decreased [57]. The method proposed in [46, 49] characterizes the probability of congestion dissipation in a given cycle depending mainly on the traffic lane capacity. Persisting congestion is related to the traffic quantity $X \geq 1$ on a single lane at intersection approach.

For estimating the residual queue lengths, when $X > 1$, the analysis time-span t_a is of essence [12, 63, 64]. The accuracy of queue length estimation, covering also residual queues depending on the analysis time-span was compared in [22]. The mean squared error (*RMSE*) value increases with the analysis time-span length t_a. Noteworthy, in the case of residual queues the *RMSE* values did no vary much being about 1.5 veh./t_a. For short time-spans it is important to accurately pre-determine the theoretical traffic capacity using the mathematical models with due regard to the driving behaviors when in the terminal period of green phase [58].

The traffic performance of a lane or whole intersection and thus both traffic engineers and drivers assess their reliability. Usually, the traffic engineers focus mostly on the peak time congestion duration, which may be estimated based on residual queue lengths and their dissipation time or by calculating the trip delay. The drivers, in turn, assess the intersection based on their perception of the queue at the intersection entry and the delay due to compromised traffic conditions. Due to an extensive range of opinions and expectations, a few congestionlevels should be applied, depending on the pre-determined congestion or traffic conditions quantities. This kind of assessment should, therefore, consider the time of reliable operation of the traffic lane from acceptable queue formation until the onset of unacceptable congestion defined by the critical queue length ($t_{N,i}$, $t_{N,i+1}$, $t_{N,k}$ in Fig. 3) persisting for the time period of $t_{zaw,i}$, $t_{zaw,i+1}$, $t_{zaw,k}$. The critical residual queue length is closely related to the queue formation process, whose characteristics depend on arrival flow volume q and its variation over time and traffic control parameters and thus the traffic capacity c [17].

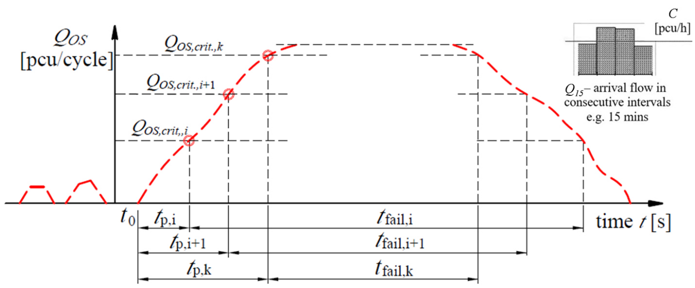

Fig. 3. Simplified analytical diagram illustrating variability of residual queue Q_{OS} in time (in the traffic peak) with a selected parabolic variability profile of the traffic flows (right). The graph indicates prior critical lengths of residual queues $Q_{OS,crit}$.

Above, Fig. 3 presents the concept of critical length of residual queues $Q_{OS,crit.}$ that are still acceptable to vehicle drivers. When the critical value is exceeded, this is indicative of the occurrence of failure. Failure time t_{fail} is called the renewal/unreliability period. In the case of lane functioning, which is renewable in time, a return to the fit/reliable state will depend on the size of the arrival flow entering the intersection, type of operation (pre-timed, actuated) and on lane capacity. The mere appearance of smaller traffic intensities still does not prove a significant improvement in traffic conditions. The situation will improve only after a while, when the residual queue length Q_{OS} is less than its critical value $Q_{OS,crit.}$.

The study presented in [10] give some insight into the single-cycle residual queue formation process. This process is illustrated in Fig. 4. Some reference to this description can be found in to in Fig. 1 showing queue formation between the signaling cycles T_{I+1} and T_{I+2}. It is commonly accepted in traffic engineering analyses that the signaling cycle starts when the signal turns red, continues through the whole red and yellow time (no entry to the intersection allowed), the following green and yellow time (i.e. the saturation period), ending when the signal turns red in the next cycle. However, for the purposes of this analysis, the combined time of red and red/yellow signals is considered equivalent to the effective red time R_e and the green and the following yellow times are considered equivalent to the effective green time G_e.

It is worth noting that in the cycle $i + 1$ we deal with the initial queue $Q_{in,I+1}$, which influences the length in distance of the queue that would form in the signaling cycle T_{i+1}. Considering the arrival flow volume in a given cycle q_{I+1}, the length of the queue formed during the effective red time increases with a rate depending on this arrival flow volume. By the end of this period when the vehicles are no longer allowed to pass the stop line the queue has the length of $Q_{SG,I+1}$, consisting of the vehicles that were part arrival flow q_{i+1} and stopped in the lane during the red time. However, the total number of vehicles queued in the lane in this time period would increase when we take into account the initial queue $Q_{IN,i+1}$. This gives the total queue length at the end of red time of the signaling cycle under analysis $Q_{re,I+1}$. When the signal turns green, allowing the vehicles to start moving, the queue discharges at a rate corresponding to the saturation volume s_{i+1}. Note that the queue does not decrease in distance due to dissipation of the platoon at front end and its extension at the rear end due to the continuing arrival of new vehicles range of the queue does not decrease due to the dispersion of the column of vehicles of the q_{I+1} flow. The queue length in distance will start to decrease in the analyzed signaling cycle T_{I+1} when the last of the queued vehicles started to move ahead. On the lapse of the $G_{e,i+1}$ the subsequent signaling cycle $i + 2$ starts. In its initial phase, the vehicles that were unable to pass through the intersection start forming the initial queue of the subsequent signaling cycle T_{i+2}. Worth noting are the following consequences of the queue formation process in $i + 1$ signaling cycle:

- with the initial queue $Q_{IN,i+1}$ being present in the cycle under analysis, an initial queue would still form in the subsequent cycle T_{i+2} even though the traffic volume q_{i+1} was smaller than the traffic capacity c_{i+1},
- there was no initial queue in the cycle T_{i+1}, the lane capacity c_{i+1} would allow complete discharge of the $Q_{\max,i+1}$ queue due to the capacity reserve of $Q'_{OS,i+1}$ (Fig. 4).

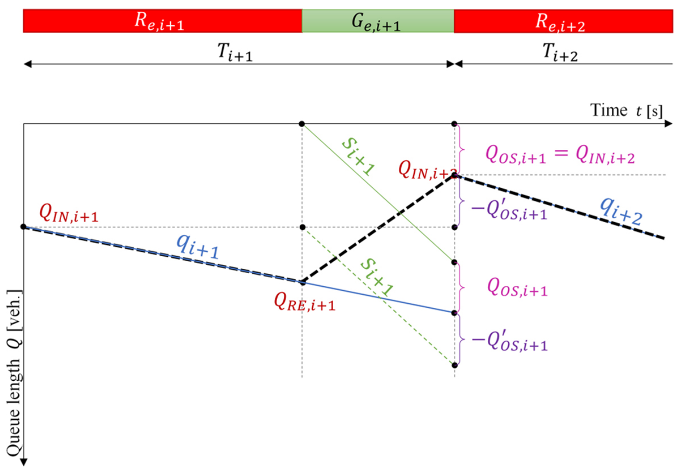

Fig. 4. Residual queue formation process after the signal turned red, based on [10]. Variables: Q'_{OS} – the potential queue length that may be discharged during the green phase (cycle capacity reserve), the rest as shown in Figure 1

These characteristics can be clearly seen when we subject to numerical analysis the process taking place in cycle T_{i+1} represented in Fig. 1.

Based on Fig. 1 and Fig. 4 it appears appropriate to distinguish two residual queue times of a given signaling cycle. The first of them is the ‘in the cycle’ queue $Q_{OS,I+1}$, whose length takes into account the traffic situation resulting from the previous cycles, thus being the subsequent cycle initial queue length $Q_{IN,i+1}$. The second of them is the ‘from the cycle’ queue $Q'_{OS,I+1}$, whose length depends solely on the arrival flow volume q_{i+1} considered in relation to the traffic capacity c_{i+1}. A negative value of Q'_{OS} indicates spare capacity in the i-th signaling cycle, in relation to the current traffic demand, expressed by the arrival flow volume q_i (apart from the fact about the initial queue). The queue discharge process was discussed more extensively in [10], while residual queue analyses can be found also in [60].

To summarize, the residual queue size is the result of the balance of inflow and outflow in a given signaling cycle. Based on the literature review and discussion of the referenced research results, it can be concluded that the process of formation and variation of the length of the queue remaining is a complex process and sensitive to slight changes in key variables. These variables are undoubtedly tributary traffic volume and throughput. However, this topic is not the concern of this article. It is an interesting issue, which the authors will try to explain in depth in a separate paper [65]. Figure 5 shows an example of residual queue length variation over time resulting from the arrival and departure flow variations.

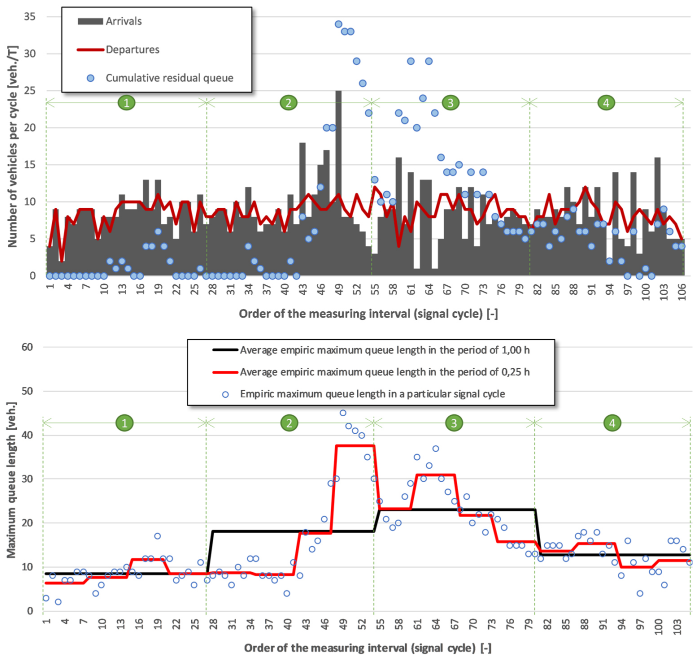

Fig. 5. Illustrative arrival and departure flow rates and the residual and maximum queue length in distance, including the mean 15- and 60-minute mean lengths (where: 1, 2, 3, 4 – measuring hour; measuring period 6:00-10:00 AM), based on [22]

The data comes from the lane of the straight-ahead traffic at the eastern approach of the Rondo Maczka intersection in Bydgoszcz. The values used in these comparisons were the observed i.e. actual residual queue lengths and the expected values obtained with theoretical determination methods, including the method given in WR-D-12 [8] (15-minute observation intervals with residual queue determination every 5 minutes and the mean queue length calculated at the end of the observation interval). This example shows how the size of the queue depends on the balance of inflow and outflow. At this intersection, the signal cycle was constant, and therefore the length of the green and red signal was also constant in each successive cycle. The queue value is strongly influenced by the type of structure of the vehicles of the stream under consideration, in addition to the inflow and outflow values themselves. The dimensions and lengths of heavy vehicles worsen the capacity of the lane, including the process of queue formation at the inlet during starting and stopping maneuvers in the queue [65].

5. Comparison of actual vs. estimated residual queue lengths

The residual queue estimation accuracy was checked using the method recommended in [8]. Based on the discussion so far, it was assumed that the most accurate residual queue determination method will be to count the queued vehicles "cycle after cycle" as soon as the signal turned red. The arrival and departure flows and control parameters were also logged during these surveys. The collected data allowed volume-to-capacity (saturation degree) rating of the surveyed locations also on cycle-by-cycle basis. The resulting database was used in further analyses to estimate residual queue lengths to identify appropriate methods for their approximate determination. These methods are described below, including estimation method details:

- M1: Q_{OS}_15, WRD – mean residual queue length estimated for 15-minute time-span as per WR-D-12 [8], i.e. an average of three queue lengths (number of queued vehicles) counted from 5-minute periods (once every 5 minutes; i.e. the last cycle of the 5-minute period);
- M2: $Q_{OS\_\text{cycle},15}$ – mean residual queue length for 15-minute time-span obtained from cycle-by-cycle queue counts;
- M3: Q_{OS_15} – residual queue counted at the end of each 15-minute time-spans (i.e. the last cycle of the 15-minute period);
- M4: $Q_{OS\_\text{cycle}\_5/15}$ – mean residual queue obtained from 3 mean residual queues in 5-minute time spans (i.e. from completed signaling cycles in a 5-minute period); each 5-minute queue length is calculated as the average of the cycle-by-cycle data.
- $X_{\_15}$ – average 15-minute volume-to-capacity degree calculated with the values determined for each of the subsequent cycles, calculated as:

$$X_{\_15} = \frac{q_{15}}{c_{15}},\ [-] \tag{5.1}$$

where: X_{15} – traffic lane volume-to-capacity ratio in 15-minutes period [–], q_{15} – empiric arrival flow volume on a given intersection entry lane [veh./0.25h], c_{15} – average lane capacity from 15-minutes period [veh./0.25h], calculated by [61].

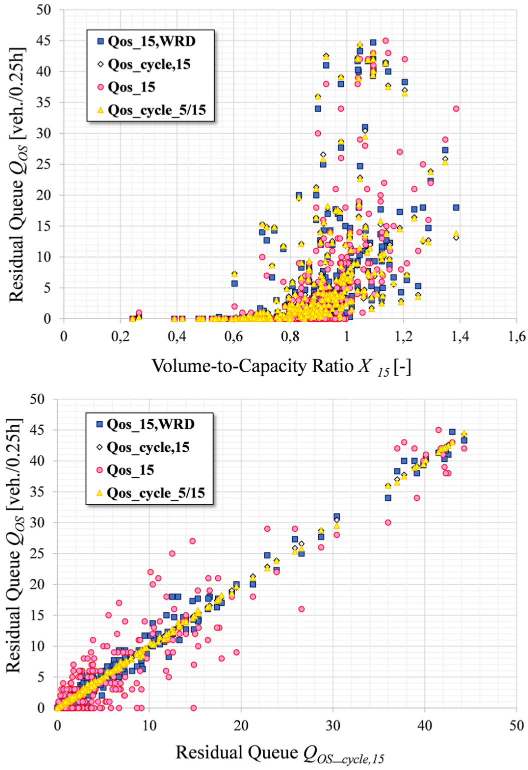

Fig. 6. Comparison of the analysed residual queue length estimation methods

The above-described M1, M3 and M4 queue estimation methods are compared to the M2 method in Fig. 6 below, which shows also the mean saturation degree $X_{\_15}$.

In the above comparisons one can see some deviations of the obtained queue lengths in relation to the most accurate cycle-by-cycle data collection method M2. The greatest deviations are observed for M3 method followed by M1, and M4 methods. Note also that the deviations increase with the saturation level. The *RMSE* for the M1 method relative to M2 were 1,1 veh., for the M3 method 3,6 veh., and for the M4 method 0,2 veh.

A non-parametric sign test was conducted in the first place. In order to verify statistically significant differences between M1, M3 and M4 methods on the one hand and M2 method (chosen as the reference method), a non-parametric test, i.e. a mark test, was performed first. The sign test considers the signs of differences between the subsequent pairs of variables ignoring the amount of these differences. This test is intended for related (interdependent) variables as the compared residual queue lengths come from the same data sample.

Generally, non-parametric tests are recommended for distributions other normal. The Wilcoxon signed-ranks test, which besides the sign of difference also considers their order and amount, was carried out for comparison purposes. The relevant comparative analyzes were conducted at significance level of $\alpha = 0.05$ in *Statistica* software program by Statsoft.

The statistical analyses were carried out for different X_15 values ranging from 0.00 to 0.69, from 0.70 to 1.00 and from 1.01 to 1.40. The boundaries of the capacity utilization rate intervals for which the suitability of the analyzed queue estimation methods was estimated were determined by observing the results of the sign test, which was conducted for the dataset by shifting the analyzed load rate interval by 0.1 (the results are illustrated in Fig. 7). The results of these analyses are given in Tables 1–3. The analyzes that showed statistically significant differences between the analyzed methods.

Table 1. Results of comparative analysis using the sign test at X_15 ranging 0.00 to 0.69

Pair of variables:	**number of unrelated**	**percent $v < V$**	***Z***	***P***
$Q_{OS\_cycle,15}$ & $Q_{OS\_15,WRD}$	24	37.500	1.021	0.307
$Q_{OS\_cycle,15}$ & Q_{OS_15}	24	16.667	3.062	0.002
$Q_{OS\_cycle,15}$ & $Q_{OS\_cycle\_5/15}$	21	*The differences between the methods are negligible* ($P > 0.950$)		

Table 2. Results of comparative analysis using the sign test at X_15 ranging 0.70 to 1.00

Pair of variables:	**number of unrelated**	**percent $v < V$**	***Z***	***P***
$Q_{OS\_cycle,15}$ & $Q_{OS\_15,WRD}$	164	37.195	3.202	0.001
$Q_{OS\_cycle,15}$ & Q_{OS_15}	165	29.091	5.294	< 0.001
$Q_{OS\_cycle,15}$ & $Q_{OS\_cycle\_5/15}$	136	38.971	2.487	0.013

Table 3. Results of comparative analysis using the sign test at X_15 ranging 1.00 to 1.40

Pair of variables:	**number of unrelated**	**percent $v < V$**	***Z***	***P***
$Q_{OS\_cycle,15}$ & $Q_{OS\_15,WRD}$	64	71.875	3.375	< 0.001
$Q_{OS\_cycle,15}$ & Q_{OS_15}	65	64.615	2.233	0.026
$Q_{OS\_cycle,15}$ & $Q_{OS\_cycle\_5/15}$	58	44.828	0.657	0.511

To confirm the above results, additional analyzes were done using the paired samples Wilcoxon test, which showed comparable results.

From the above-mentioned statistical analysis of comparisons to M2, it transpires that:

- M1, and M4 methods may be used alternatively for small and medium values of X_15 falling in the range of 0.00 to 0.69 (i.e. in traffic conditions where residual queues appear rather sporadically and are the result of a purely random flow of vehicles);
- none of the methods is the option of choice for X_15 values in the range of 0.7 to 1.00 (i.e., in traffic conditions where residual queues occur due to large fluctuations in traffic);

- Either M4 method may be used for high X_15 i.e. 1.01 to 1.4 (i.e. in traffic conditions where residual queues always appear and are the result of greater demand than transport supply).

The differences between the M1, M3 and M4 methods and the M2 method featuring the most accurate cycle-by-cycle data collection are visualized in the graphs in Fig. 7.

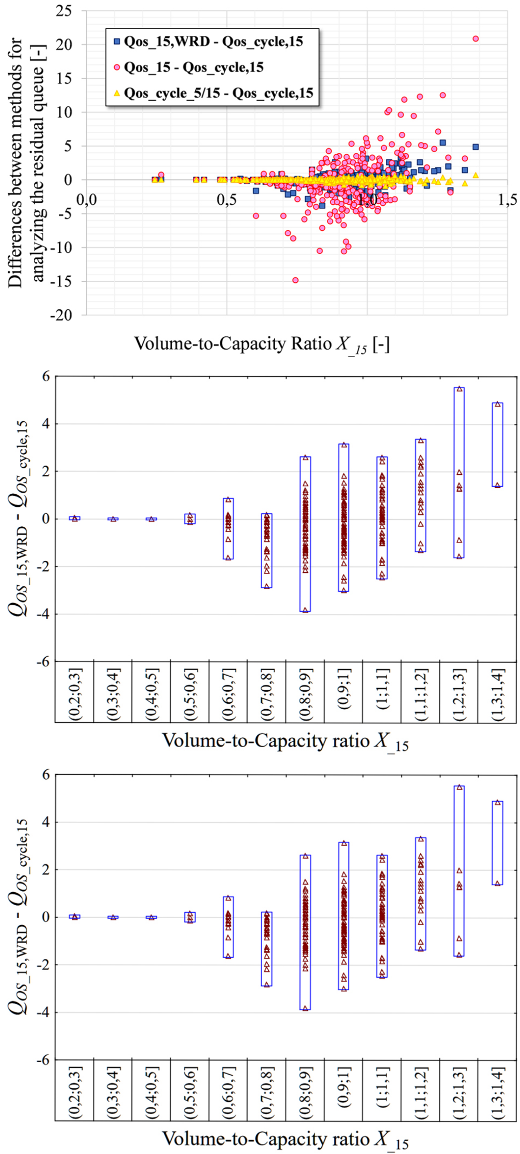

Fig. 7. Residual queue estimation methods M1, M3, and M4 compared to the accurate data collection method M2

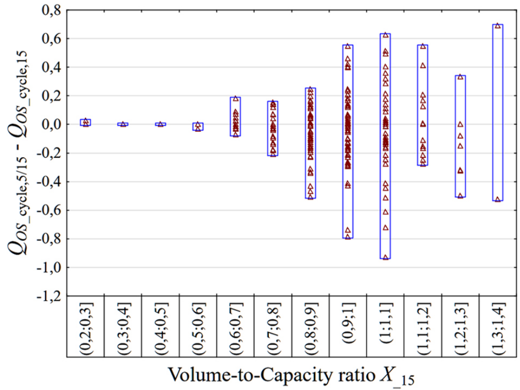

Fig. 7. [cont.]

It is worth noting at this point that generally the M1 method underestimates the queue lengths for $X_{\_15}$ values the range of 0.6 to 0.8 overestimating them for $X_{\_15}$ values higher than 1.1. Also, the M3 method underestimates the queue lengths for $X_{\_15}$ values the range of 0.6 to 0.9 overestimating them for $X_{\_15}$ values higher than 1.0. The closest to M2 is the M4 method, giving values fluctuating about the M2 results. The greatest absolute deviations from the M2 values were obtained with the M3 method, followed by M1 and M4, for which the deviations were the smallest.

The *RMSE* values of the tested methods relative to the M2 were for the whole sample about 1.1 veh. for M1, 3.6 veh. for M3 and 0.2 veh. for M4. Thus, it can be concluded that the method of analysis included in [8] is less accurate than, for example, the M4 approach (in analyses centered on specific ranges of X values).

6. Conclusions

Residual queue length is a traffic quantity indicating, in the first place, volume-to-capacity ratio of signalized intersections. Presence of queued vehicles indicates exceeding of the traffic capacity of a single traffic lane or a group of traffic lanes. Sometimes, this may be a situation of temporary congestion with the queues alternately building up and discharging due to random variation of the arrival traffic volume. Continuous inflow of excessive traffic volume may, in turn, lead to persisting traffic jam. In practical engineering, 15-minute or hourly intervals are used (rather than shorter periods) for the purposes of analyzing and rating the intersection capacity, level of service and performance. When the queues persist, lasting over subsequent intervals we deal with a traffic jam situation whose duration depends on the momentary X ratings for so long as the arrival flow remains at least equal to the intersection traffic capacity.

The objective of this article was to verify the recommendations given in the WR-D's manuals [8] as to the preferred residual queue estimation method. The authors analyses have shown that the proposed queue length estimation method (M1) is not accurate enough and shows statistically significant deviations from the most accurate results obtained with the M2 method, in which the residual queues are counted cycle by cycle. It was also demonstrated that the M3 method gives overestimated values at high X values.

Therefore, with no empirical data in hand on queue lengths between successive signaling cycles, the method proposed in [2, 53] should be used. The research [9] show the most accurate estimation of the queue lengths using this method. That is an option of choice, for estimating the residual queue lengths, based on the X values for the adopted 15-minute or hourly interval. Adequate traffic volume data are of essence in this case which should relate to the arrival flow rather than the flow that has passed through. In cases where field surveys are desired, residual queues should be determined for the adopted observation interval as an average of the values obtained in the subsequent signaling cycles. Depending on purpose of the analyses the M2 method determining the residual queue lengths in subsequent cycles allows determination of other traffic quantities such as residual queue percentiles, for example 50%, 75%, 85% or 95%. That said, the preferred methods are of course those, in which the residual queue lengths are determined directly for a given traffic lane for each signaling cycle, including accurate determination of the traffic composition and movements.

The most difficult dilemma of the method for residual queues, both M1 proposed in [8] and the others (M2, M3, M4), is the fact about the lack of basic data on the generic and directional structure of the vehicles in these queues. This fact, according to the authors, is the most significant from the point of view of using transportation demand data to accurately determine traffic volumes at signalized intersections. Therefore, unequivocally, the authors recommend accurately calculating the number of vehicles in queues along with their type and directional structure.

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Dylematy poprawnego szacowania długości kolejek pojazdów w analizach przepustowości skrzyżowań

Słowa kluczowe: kolejki pojazdów, sygnalizacja świetlna, pomiary ruchu drogowego

Streszczenie:

Kolejki pozostające są jedną z podstawowych wielkości miar warunków ruchu drogowych skrzyżowań wyposażonych w sygnalizację świetlną. Kolejki te parametryzują stan zatoru drogowego, tzn. świadczą o przeciążeniu ruchowym. Dokładne oszacowanie długości kolejki jest istotną częścią oceny wydajności tych skrzyżowań oraz układu drogowego oraz podejmowanych kierunków usprawnień podejmowanych na ich podstawie. Jest to szczególnie ważne w projektowaniu geometrycznym skrzyżowań oraz w analizach zatłoczenia arterii. Przedstawione w artykule analizy i porównania odnoszą się głównie do nowych polskich wytycznych wykonywania pomiarów ruchu drogowego (WR-D-12), odnoszących się m.in. do badań kolejek na skrzyżowaniach z sygnalizacją świetlną. Sprawdzono również alternatywne sposoby szacowania kolejek pod kątem ich dokładności. Pierwsza część artykułu zawiera przegląd literatury dotyczącej metod estymacji kolejek. Następnie scharakteryzowano wyniki badań własnych, aby pokazać złożoność zagadnienia kolejek pozostających, formujących się na skrzyżowaniach z sygnalizacją świetlną. W dalszej części przeanalizowano różne sposoby określania tych kolejek pojazdów, w tym zawarte w WR-D-12. Na tym etapie przeprowadzono analizę porównawczą danych empirycznych uzyskanych z kilku skrzyżowań. Ostatnia część artykułu zawiera wnioski i zalecenia autorów dotyczące prawidłowego szacowania oraz dokładnego określania długości kolejek pozostających na potrzeby analiz przepustowości.

Received: 2023-12-01, Revised: 2024-02-27