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# ASSESSMENT OF SELECTED METHODS OF ESTIMATING THE MAXIMUM BACK-OF-QUEUE SIZE ON A SIGNAL-CONTROLLED INTERSECTION APPROACH

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**Abstract** – The article presents the characteristics and evaluation of the accuracy of estimating the maximum length of the queue of vehicles at signalized intersections by commonly used methods in the world. The analyzes were based on the latest editions of the guidelines in the United States, Canada, Australia, Germany and Poland.
In order to carry out accuracy analyzes, traffic tests were carried out at 5 intersection inlets in three different cities in Poland (Bydgoszcz, Torun, Warsaw), covering all phases of vehicle queue formation during individual periods of the signaling cycle (effective red and green signal). In total, the analysis had the results of tests from 81 hours of observation ~23,000 behaviors of vehicle drivers.
Based on the analyzes it was found in particular:

- slight differences in the construction of mathematical models of the considered calculation methods, with the exception of the US HCM model from 2016,
- small errors in estimating the maximum queue length in unsaturated vehicle flow states (~3-5 vehicles/cycle and ~2-6 vehicles/15 minutes interval),
- quite large errors in estimating the maximum queue length in saturated and oversaturated vehicle flow states (~11-16 vehicles/cycle and ~15-18 vehicles/15 minutes interval)
- the main impact on estimation errors in oversaturation traffic states is not taking into account or incorrect determination of the 'so-called' initial queue length of the period preceding the analyzed period.

**Key words** – back-of-queue size, signal-controlled intersection, traffic engineering

**JEL Classification** – R41

## INTRODUCTION

Human functioning is inseparably connected with road transport in current socio-economic conditions in large and medium-sized urban centers. This fact is undoubtedly confirmed by annual data on the ever-increasing automotive index in economically developed and developing countries [4, 21]. More and more often, as a society, we feel discomfort related to the growing problems resulting from too many vehicles present on the urban road network. Thus, we realize the need to answer the question: in what direction should city transport systems be developed?

The search for optimal ways to eliminate or reduce congestion on urban road networks requires thorough knowledge of the processes of these extreme states and their suppression. The oversaturation of traffic on the urban road network, and thus the formation of queues of vehicles waiting for transport service, occurs mainly during periods of greatest demand for movement - in traffic peaks. Road system overloads occur mainly at intersection inlets, due to their insufficient capacity in relation to the volume of arrival traffic flows. Hence the practical knowledge of accurately determining the length and range of vehicle queues is particularly important at three stages of traffic engineering activities, i.e. intersection design, traffic light programming and traffic management.

The purpose of the article is to present a comparative analysis of the most commonly used mathematical models in the world for calculating the length of vehicle queues at intersection inlets with traffic lights. This analysis was performed after field tests of the process the formation process and the volatility of queue lengths on individual lanes at 5 signalized intersection inlets of several Polish cities. Also, an assessment of the accuracy of estimating the maximum states of vehicle queues using the verified models was performed (the so-called „maximum back-of-queue”).

The first chapter contains a synthetic description of the calculation models used to estimate the maximum length of vehicle queues at intersections with traffic lights (so-called back-of-queue size). The second chapter describes the analysis of the formation process and the volatility of queue lengths on signalized intersection approach. This description details the elements that should be taken into account in the analysis of estimating the maximum size of the queues. The third chapter contains a description of the testing ground and the research methodology. In the fourth chapter, theoretical results of estimating the size of queues, determined with the use of the available models described in chapter 2, were compared with each other. Then, the results of calculations were compared with respect to the empirical results, comparing the differences obtained between the results of estimating with different models. At the end of the article, there is a discussion on the results and conclusions resulting from the obtained results of comparative analyzes.

## 1. SYNTHESIS OF MAXIMUM BACK-OF QUEUE MODELS AND PROCESS

It is assumed that the queue forming process is divided into two phases of a single average signalling cycle of the analyzed period of analysis (e.g. hour or quarter hour). This was noticed in all mathematical models regarding the length of vehicle queues included in the most popular (according to the author) road design guidelines in the world (from the United States [11], Germany [9-10], Australia [2, 7-8], Great Britain [19], Canada [3]) and also in Poland [5-6]. These periods correspond to the time intervals at the beginning and end of the green signal transmission time. In these intervals we note respectively the so-called queue of "stopped vehicles" due to the red signal interval and "remaining queue". Hence (generally), length of a vehicle queue comes down to determining:

- the length of the remaining queue $Q_{OS}$ (“*OverSaturated”*), expresses the number of vehicles registered at the end of the green signal in front of the inlet stop line and indicates volume of traffic congestion at the signalized intersection inlet; the queue is formed of vehicles that did not manage to leave the intersection inlet during the period of the green signal time of the average signalling cycle due to the conditions of overrsaturated arrival flow rate (excess demand over transport supply) or due to random fluctuations in the arrival flow rate;
- the length of the queue forming during red signal time $Q_{RE}$ (“*Red Effective”*), expresses the number of vehicles usually registered at the beginning of the green signal, arranged from the stop line at the inlet to the last vehicle joining the queue at the time when the vehicles from the beginning of the queue are already moving and the vehicles from its end have not yet started (this queue may also be formed later in the green light period or in the next cycle with significant traffic overloads); the length of this queue does not take into account the length of the remaining queue and applies only to the process of its formation due to an effective red signal.

The sum of this two terms of queue is the length of maximum queue range in analysis (maximum back-of-queue $Q_{max}$). This is the longest queue in terms of its size that can be created in a given signalling cycle.

Some of the guidelines also distinguish a different term of the vehicle queue, formed only from commuting vehicles during the effective red signal, but without its extension due to the inertia of the queue at the time of starting-up vehicles from stop line at intersection inlet (it is calculated directly as the multiplication of the effective red time and the arrival flow rate, $Q_{SG}$, „*Start of Green Signal*”). In turn, the third term of queue was introduced to the calculation model of maximum back-of-queue only as part of the latest update of US guidelines [12-13]. It is a queue formed at the beginning of the red light of the analyzed cycle, and formed of vehicles "remaining from the period preceding the analyzed period". This third type of queue is called the "initial queue" $Q_{IN}$. Inclusion this term of queue in the calculations results in an extension of the estimated maximum back-of-queue length for the considered analysis period due to the presence of an additional number of vehicles at the intersection inlet that was not served in the period preceding the analyzed period. It is worth emphasizing that the length of the initial queue is also taken into account by some of the guidelines (e.g. Polish [5]), but only in multi-interval models of delay.

## 2. The complexity of the process in the context of selected mathematical models

The terms of queues listed above are schematically illustrated in Figure 1, in the considered analysis divided into four successive signalling cycles (based on the author's research results).

In relation to the most popular mathematical models in the world (according to the author), which are used to estimate individual elements of the maximum back-of-queue size, there are quite significant differences in the theoretical and actual process. This applies to the following:

1. The back-of-queue is determined for the average signalling cycle in the considered period of analysis, for averaged traffic control parameters as well as for the volume of arrival flow rate and capacity; this may have a significant impact on extreme traffic conditions during peak traffic periods in urban areas.
2. The queue forming on red light $Q_{RE}$ is based on the vehicle service system knowing about arrival flow $q$ and saturation flow $s$, while in fact the number of vehicles in the queue changes throughout the entire signalling cycle - on the basis of stops, starts and the inertia of their intensities (e.g. not all vehicles start-up at the same time when starting green signal transmission or vehicles that are not serviced are in queue and are in motion at the beginning of the next cycle. This method is based on the theory derived by Webster (originally for determining the average delay) [22]. It results from the assumptions and geometrical relationships of the service of arrivals during a single signalling cycle, conventionally divided into two periods: an effective red and green signal; after appropriate transformations, the final form of the pattern is identical to that in many guidelines [2-3, 5, 7-9, 19]. All modifications of this pattern result only from different characteristics and assumed conditions of the inflow stream movement [10-11]. The model of this queue includes vehicles completely stopped. A different mathematical model appears only in US guidelines [12-13], based on detailed data on the arrival flow (separately for red and green light) and, among others on the characteristics of vehicle acceleration when starting, stopping or speed of crossing the intersection.

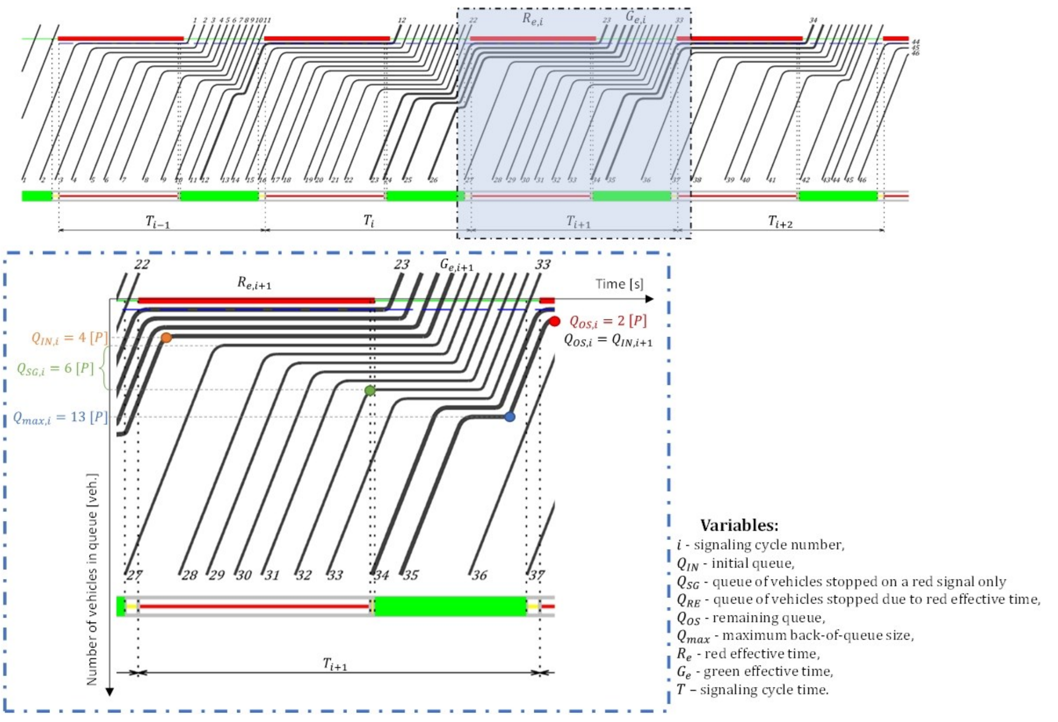



**Fig. 1. Formation process diagram of the maximum back-of-queue size $Q_{max}$ including its terms**

3. The remaining queue model is still based on the results of work [1, 16-17, 23], and the idea of the model for determining these queues is practically the same in all guidelines. In [17], the author used the 'so-called' technique of transforming the coordinates of the stochastic state of delays in relation to the delays curve for the deterministic state. A detailed method for determining this mathematical model has been presented, among others at work [23]. The idea of modelling the average remaining queue is coincides with the model presented in the paper [1] in almost all guidelines (e.g. in [2, 9]). This form of the model was also recommended for calculations in Poland in older unofficial guidelines [20]. In other countries, the remaining queue models used differ only in the respective coefficients used to correct the accuracy of calculations (e.g. in [9-10, 11-13]). It can be presumed that this model should "somehow" take into account traffic congestion during the considered analysis period, taking into account in the remaining queue the effect of moving the length of the initial queue between successive signalling cycles. However, it does not take into account the state before the considered analysis period (except for the model derived from the guidelines [11]).
4. Determining the initial queue (in US only) results from a simple calculation of the surplus between the number of vehicles reporting for service and the number of vehicles that can be handled during the period of analysis. The length of this queue is always determined in multi-interval analyzes, between successive sampling intervals (analysis sub-periods). Only US guidelines [12-13] include this queue element, taking into account both the possibility of increasing and decreasing the maximum length of the queue due to the appearance of the initial queue in a given period of analysis.
5. The models do not take into account the intensity of starting-up vehicles in the back-of-queue and the intensity of stopping vehicles in the initial queue, accepting notifications and service of vehicles directly from the inflow and outflow rates.

The situation of the vehicle queue formation process in four consecutive signalling cycles in Figure 1 contains much more detail than the number of variables in the mathematical models studied. To approximate the complexity of the vehicle queue formation process, the *i*+1 cycle was isolated for analysis. We deal with 4 vehicles in the initial queue (preceding the analyzed cycle), which were unable to leave the intersection during the green signal interval. Therefore they form an important part of the queue in analized cycle. Of the arrivals (reporting to service) in the analyzed *i*+1 cycle, 9 of them perform stopping due to red signal interval, but only 6 of them perform stopping manoeuvre during effective red signal time. After the start of the green signal interval, 3 more vehicles stopped during the effective green signal period. Interestingly, if it had not been for the initial queue of 4 vehicles remaining after the previous cycle *i*, the last 3 vehicles from the arrival flow in cycle *i*+1 would not have stopped the stopping manoeuvre probably. Continuing, the intersection inlet capacity allows 11 vehicles to be servised while the green signal time. So, all of arrival vehicles for service in this *i*+1 cycle would be served if there were no initial queue at the intersection inlet. Moreover, the last vehicles from the inflow would not take part in the queue forming process (they would not stop). But, there is insufficient capacity for all vehicles noticed due to the initial queue in this analized cycle. Because the excess of demand over supply is 2 vehicles, it should be noted as the remaining queue from this analysis period. Ultimately, the results are as follows for the considered *i*+1 cycle:

- the initial queue $Q_{IN,i+1}$ = 4 veh.,
- the maximum back-of-queue $Q_{max,i+1}$ = 13 veh.,
- the remaining queue $Q_{OS,i+1}$ = 2 veh.

The discussed process of vehicles from the queue can also be represented by the graph in Figure 2.

From this drawing, the complexity of the initial queue in the process of forming the maximum back-of-queue can be clearly seen. Arrival flow curves ($q_{i+1}$) and departure flow curves ($s_{i+1}$) did not intersect. They depict the intensity of vehicles approaching the intersection inlet and vehicles leaving the intersection. Hence there will be a surplus of demand over supply during this period - the remaining queue. This is because of the initial queue formed at the beginning of the red signal interval of *i*+1 cycle. However, if the initial queue were not present, the inflow $q_{i+1}$ and outflow $s_{i+1}$ curves would intersect. So we would have the case of capacity reserves (presented as $Q_X$ for servicing 2 vehicles – see $q^*_{i+1}$ curve and $s^*_{i+1}$ curve). Figure 2 also shows an illustration of the moment in which the queue was formed from stopped vehicles at the end of the red effective signal ($Q_{STOP}$) and a queue formed as a result of transmitting the red signal after starting the green signal transmission ($Q_{RE}$). Model for determining the remaining queue length ($Q_{OS}$) is determined in a different way than the schematic illustration of this figure in Figure 2, which is shown by the variable $Q'_{OS}$ (based on [11-13]).Considering the above, in the context of research into the process of vehicle queue formation, the author of the article poses the question: is the accuracy of determining the maximum state of the vehicle queue at an acceptable level in engineering applications today?

## 3. DESCRIPTION OF FIELD RESEARCH

Road sections were selected as the testing ground, which were characterized by the following assumptions in the area of access to the inlet and the inlet of the intersection itself:

- typical road traffic organization with traffic lights,
- no collision of the traffic stream leaving the intersection with other traffic streams (vehicles or pedestrians) during green signal interval,
- high variability of the arrival flow rate to the inlet intersection (changing traffic conditions, both unsaturated as well as saturated and oversaturated, even traffic gridlock),
- no side entries and exits, no parking.

Five intersections in three Polish cities were selected for research, significantly different from each other in terms of characteristics related to the transport attractiveness of these cities (e.g. population density, motorization index, traffic volume, etc.). These were the cities of Bydgoszcz, Torun and Warsaw. Measurements were carried out only in favourable weather conditions (no rain, no fog, dry road, air temperature above $10^0$ C).

The detailed research methodology was characterized in [14]. The observations consisted in collecting the video material on video cameras arranged along the road of a given intersection inlet. Each manoeuvre performed by vehicle drivers in the queuing process based on 9 video paths simultaneously was identified, including the parameters of the inflow, outflow, starting, and stopping parameters. The main condition was to ensure the measurement of all phases of the vehicle queue formation process, synchronized exactly with all traffic light signals in each signalling cycle. An example photo of the testing ground is in Figure 3.

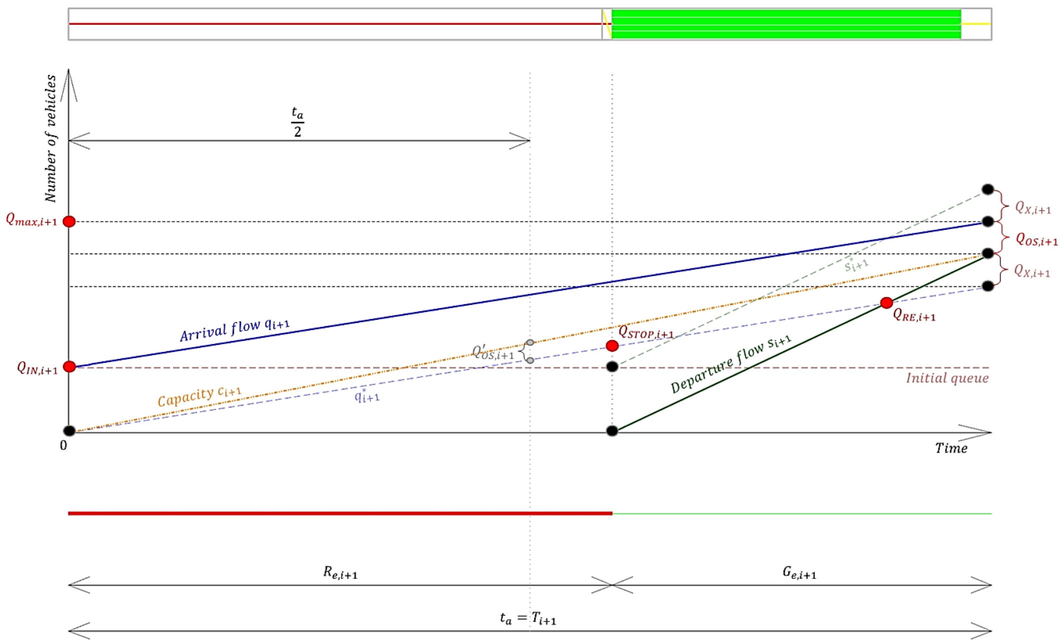



**Fig. 2. The process of forming the maximum back-of-queue size in i+1 cycle**

(explanations of variables: $t_a$ – analysis period duration, $i$ – sampling interval number, $T$ – cycle length, $R_e$ – effective red signal length, $G_e$ – effective green signal length, $q$ – arrival rate, $s$ – saturation flow, $c$ – capacity, $Q_{IN}$ – initial queue, $Q_{STOP}$ – queue of forming from stopped vehicles during the red signal only, $Q_{RE}$ – queue of forming from stopped vehicles due to a red signal, $Q_{OS}$ – remaining queue, $Q_{max}$ – maximum back-of-queue, $Q_X$ – capacity reserve – unused ability to service potential vehicles from queue)

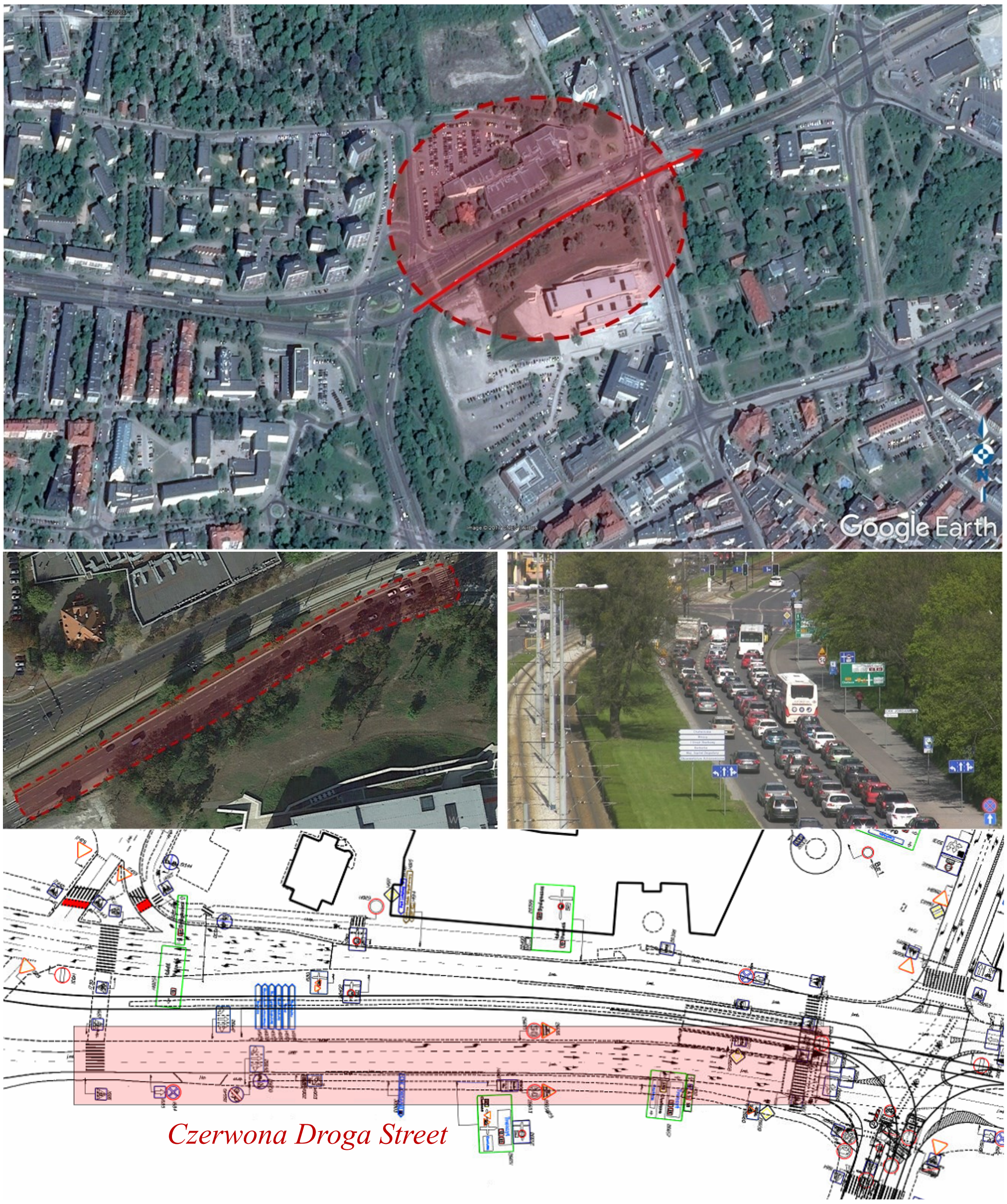



**Fig. 3. Location of testing ground no.4: city Torun, PL, inlet Czerwona Droga Street** (**west**), **intersection: Czerwona Droga st. – Aleja Solidarności st. – Odrodzenia st. – Szosa Chełmińska st.** [**53°00'54.3"N 18°36'07.1"E**] (Source: own based on Google Earth and WZDR SYSTEM)

The research material from 5 measurement testing grounds included over 75 hours of recordings, which translated into 2,178 analyzed signalling cycles, in which 22,838 vehicles were recorded, performing a total of 94,461 manoeuvres in queues. The studies reported 52.57% cycles in saturated and oversaturated traffic conditions and 47.43% cycles in unsaturated traffic conditions.

## 4. COMPARISON AND ASSESSMENT OF METHODS SELECTED FOR ANALYSIS

*Comparison of models and theoretical results*

The following calculation methods were selected in comparative analyzes with empirical results:

- Austroads Guide to Traffic Management from 2013 i 2020 (AGTM)
- Canadian Capacity Guide from 2008 (CCG)
- Highway Capacity Manual from 2000 and from 2010, 2016 (HCM),
- Handbuch für die Bemessung von Straßenverkehrsanlagen from 2015 (HBS)
- „Metoda Obliczania Przepustowości Skrzyżowań z Sygnalizacją Świetlną" from 2004 (MOPSS) – *„The method of calculating capacity of signalized intersections in Poland"*.

While studying the aforementioned mathematical models of estimating the queue of vehicles, no significant differences were observed that could affect the final result of the calculations (in terms of local road and traffic conditions in Poland, legal conditions or transport behaviour of residents). The constructions of these models are rather universal.

At this stage of the analysis, a comparison was made of methods to estimate the maximum back-of-queue size for determined output values. The methods of calculation analyzed were the methods used in the guidelines of the following countries: USA [13], Australia [8], Canada [3], Germany [10], Poland [5] and, due to the wide scope of application in the world, the HCM-2000 [11].

The results of the analysis, depending on the volume-to-capacity ratio *X*, are presented in Figure 4. The initial conditions adopted for analysis included the following variable values:

- saturation flow $S$ = 1800 veh./h,
- analysis period duration $t_a$ = 0,25 h,
- effective green time $G_e$ = 30 s,
- cycle length $T$ = 75 s,
- incremental delay factor $r_s$ = 0,50,
- upstream filtering adjustment factor $w_s$ = 0,50,
- progression adjustment factor $PF_2$ = 1,00,
- acceleration–deceleration delay $d_a$ = 8,61 s,
- initial queue size $Q_{In}$ = 0 veh.

A comparative analysis for the given initial values allowed to state that the results of calculations by methods from Poland [5] and Australia [8] show practically the same results of calculations. Similar values of estimating the length of vehicle queues were also obtained for models from Germany [10] and for the HCM-2000 method [70], whose values were comparable with the values for methods from Poland and Australia in the scope of *X* to about 1.20. After exceeding this value of volume-to-capacity ratio, for the German and US methods from 2000, slight differences in the estimated values were noted relative to the Polish and Australian methods, for *X* = 1.4, less results were obtained by about 5 vehicles. Completely different estimation was demonstrated for the Canadian method [3] and for the method currently used in United States (HCM-2016) [13].

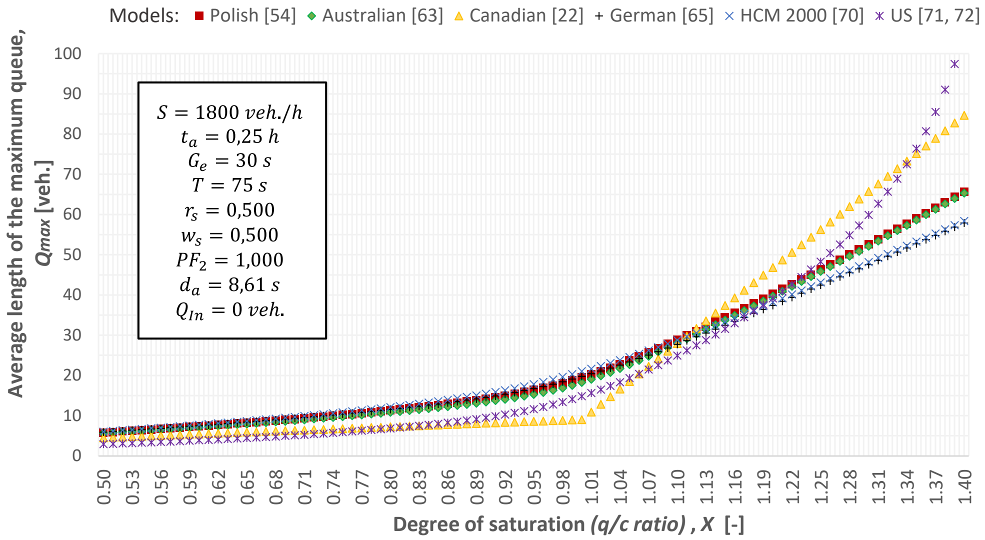



**Fig. 4. Comparison of results of calculations of the average maximum back-of-queue size according to selected methods for the adopted initial conditions**

In the first case, the course of the estimation results, depending on the increase in the volume-to-capacity ratio *X*, depends on the deterministic value of remaining queue. In the Canadian method, the length of this queue is estimated only in the conditions of saturated and oversaturated traffic conditions, i.e. when the value of $X = 1.0$ is exceeded. In addition, the deterministic approach in estimating the length of the remaining queue has a completely different dynamics, as in the case of the other methods of estimation analyzed. On the other hand, in the case of the last model under consideration, i.e. the latest HCM method, there is a clear difference in the results of the calculations due to the different model for estimating the number of vehicles in the queue formed during the effective red signal time. Up to the value $X = 1.0$, the length of the maximum queue is noticeably smaller than for other estimation methods (except for the Canadian method). However, after exceeding this value of $X > 1.0$ a more dynamic increase in the maximum queue length was noticed due to the increasing traffic demand. In oversaturation conditions, when $X = 1.4$, the maximum queue length estimated by the US method from 2016 (and 2010) is almost twice as long as the maximum queue length obtained using mathematical models from other countries (also except the Canadian model). It should be noted that this result was obtained excluding the initial queue. It is noted that these are averaged results for average variable parameters in relation to a single signalling cycle in the adopted analysis period duration $t_a$.

*<u>Comparison of empirical results with estimated results</u>*

An example of the time distribution of the maximum lengths of vehicle queues $Q_{max}$ observed in the field and calculated using the Polish method [5] in individual signalling cycles, along with the distribution of residues, are presented in Figure 5. In contrast, Table 1 summarizes the mean square estimation errors (RMSE) of the maximum back-of-queue size for methods subjected to comparative analysis and for various states of traffic state.

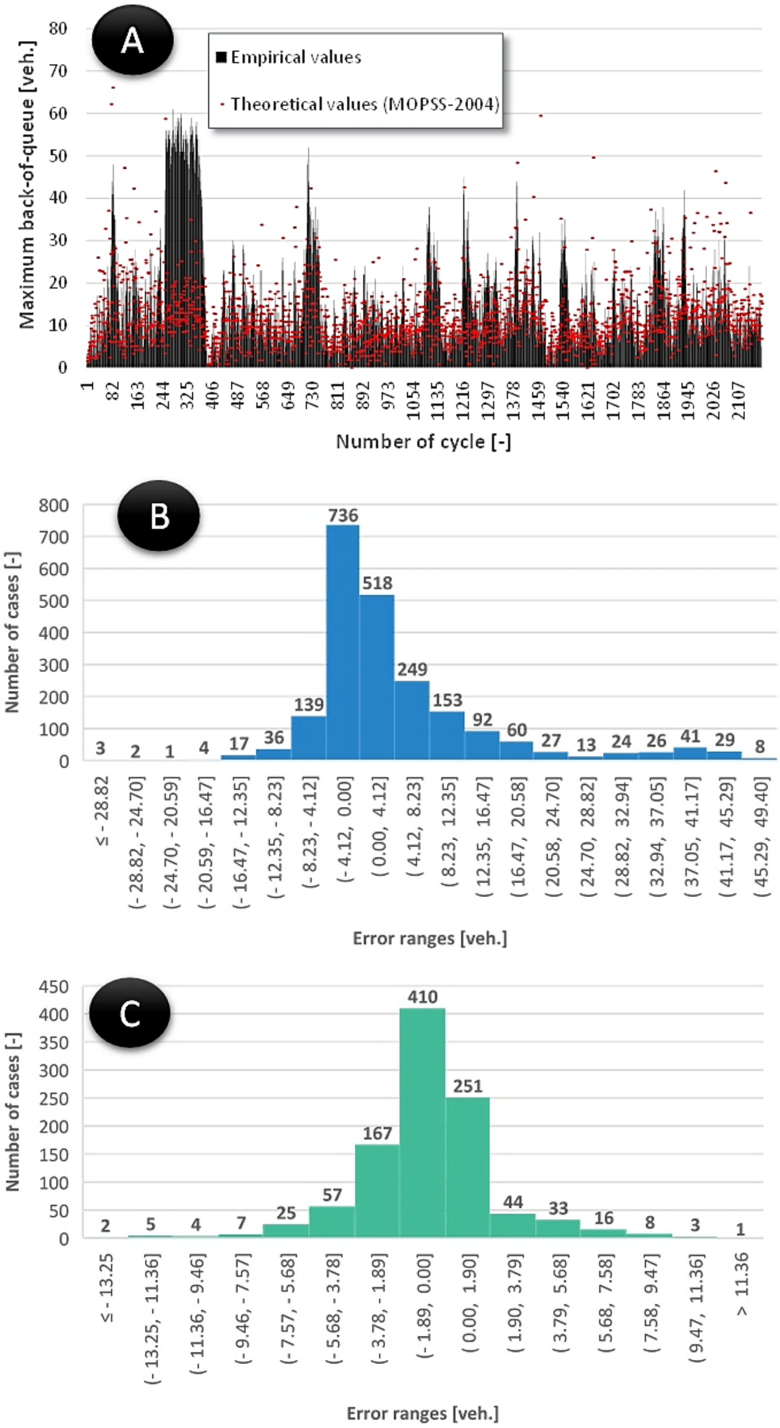
Based on the comparison of all test results, it was found that the methods of estimating the maximum range of the vehicle queue, despite several differences in calculation models, give different estimation results in the general analysis, but at a comparable error level (~ 12 vehicles per signalling cycle). A significant exception to estimation using the US method should be noted here (HCM), which includes an additional initial queue length estimator $Q_{IN}$ omitted in the other calculation methods. However, the average square error of estimation remains similar for these methods. So the obvious question is: does taking into account the length of the initial queue matter and is it needed?

When performing a more detailed analysis of the obtained results of the comparison of empirical and calculation data of the maximum length of the vehicle queue on the considered lanes, it was noticed that in the conditions of unsaturated flow of the vehicle stream at the inlet ($X < 1.0$), the results of the calculations are quite similar to the real values.

**Table 1. Summary of root mean square errors in estimating the average maximum back-of-queue size coverage in a given analysis period duration ta** [**veh.**]

| No | Guidelines: | Flow conditions at the intersection approach: | | |
|---|---|---|---|---|
| | | all together | unsaturated | over- and saturated |
| | Sampling (analysis) period: single signalling cycle $t_a = T$ | | | |
| 1. | US method (HCM-2000) [11] | 15,2090 | 3,3206 | 22,9022 |
| 2. | US method (HCM 2016) [13] | 12,3849 | 4,3282 | 18,3055 |
| 3. | Australian method (AGTM-2013) [8] | 11,3065 | 5,2376 | 14,7735 |
| 4. | Canadian method (CCG-2008) [3] | 11,6255 | 2,8656 | 15,7944 |
| 5. | German method (HBS-2015) [10] | 11,5787 | 2,6795 | 15,7584 |
| 6. | Polish method (MOPSS-2004) [5] | 11,5930 | 2,8425 | 15,7528 |
| | Sampling (analysis) period: 15 minutes $t_a = 0,25$ h | | | |
| 1. | US method (HCM-2000) [11] | 13,8797 | 1,8840 | 27,3717 |
| 2. | US method (HCM 2016) [13] | 10,6752 | 4,9436 | 20,5293 |
| 3. | Australian method (AGTM-2013) [8] | 9,0240 | 3,6170 | 14,5874 |
| 4. | Canadian method (CCG-2008) [3] | 10,0691 | 1,7528 | 16,2123 |
| 5. | German method (HBS-2015) [10] | 9,7603 | 1,7425 | 17,0501 |
| 6. | Polish method (MOPSS-2004) [5] | 9,7614 | 1,6823 | 16,8783 |

**Source**: own study based on models: [3, 5, 8, 10-11, 13]


A
Empirical values
Theoretical values (MOPSS-2004)
Maximum back-of-queue [veh.]
0
10
20
30
40
50
60
70
80
1
82
163
244
325
406
487
568
649
730
811
892
973
1054
1135
1216
1297
1378
1459
1540
1621
1702
1783
1864
1945
2026
2107
Number of cycle [-]
B
Number of cases [-]
0
100
200
300
400
500
600
700
800
3
2
1
4
17
36
139
736
518
249
153
92
60
27
13
24
26
41
29
8
≤ - 28.82
(- 28.82, - 24.70]
(- 24.70, - 20.59]
(- 20.59, - 16.47]
(- 16.47, - 12.35]
(- 12.35, - 8.23]
(- 8.23, - 4.12]
(- 4.12, 0.00]
( 0.00, 4.12]
( 4.12, 8.23]
( 8.23, 12.35]
( 12.35, 16.47]
( 16.47, 20.58]
( 20.58, 24.70]
( 24.70, 28.82]
( 28.82, 32.94]
( 32.94, 37.05]
( 37.05, 41.17]
( 41.17, 45.29]
( 45.29, 49.40]
Error ranges [veh.]
C
Number of cases [-]
0
50
100
150
200
250
300
350
400
450
2
5
4
7
25
57
167
410
251
44
33
16
8
3
1
≤ - 13.25
(- 13.25, - 11.36]
(- 11.36, - 9.46]
(- 9.46, - 7.57]
(- 7.57, - 5.68]
(- 5.68, - 3.78]
(- 3.78, - 1.89]
(- 1.89, 0.00]
( 0.00, 1.90]
( 1.90, 3.79]
( 3.79, 5.68]
( 5.68, 7.58]
( 7.58, 9.47]
( 9.47, 11.36]
> 11.36
Error ranges [veh.]

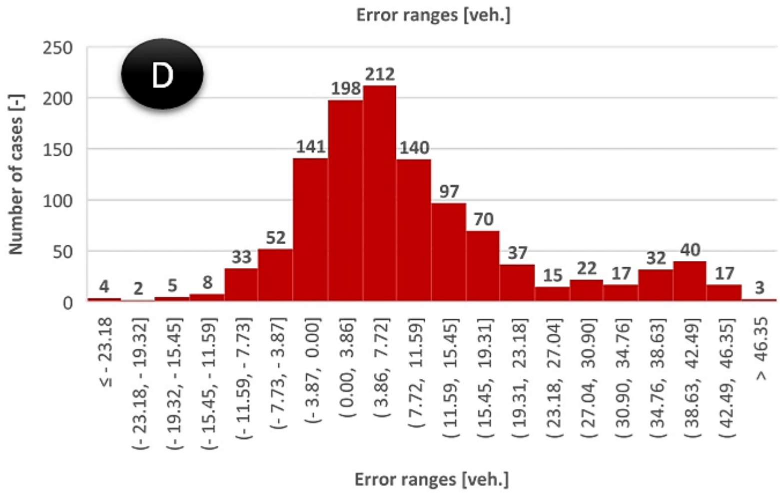



**Fig. 5. Time distribution of maximum queues of real vehicles and calculated results using the Polish method [5] (A) along with the distribution of estimation errors: for the whole sample (B), unsaturated traffic conditions (C), saturated and oversaturated traffic conditions (D)**

Calculation errors for these traffic conditions are not large and amount to about 3 ÷ 6 vehicles, depending on the chosen calculation method and the analysis period duration. But, it should be noted here, that the largest value of the calculation error was determined for the American method of 2016. This is likely to be affected by the understated value of the length of the queue forming at the intersection inlet (lane) during red signal interval ($Q_{RE}$), as described earlier - see the analysis of the results presented in Figure 4.

In turn, average square errors in estimating the maximum ranges of queues in the conditions of saturated and oversaturated traffic ($X \geq 1.0$) considered very large. In most cases, these errors reach 16 vehicles for one signalling cycle and about 18 vehicles for an analysis with a analysis period duration of 15 minutes. Both American methods of HCM estimation (2000, 2016), taking into account the presence of the initial queue, definitely overestimated the length of the maximum queue in states of persistent oversaturation at intersections. The other methods did underestimate the result of the maximum queue for this characteristic period of analysis in urbanized areas.

Despite the significant advantage of building the HCM-2016 model over the other methods, it was also decided to check the correctness of determining the length of the initial queue $Q_{IN}$. It was recognized on the basis of these analyzes that the method of estimating this queue incorrectly takes into account its accumulation proces (*QAP*) and the process of "absorbing vehicles from the remaining queue" during the selected period of analysis and during the existence of capacity reserves (sufficient length of green signal time at the inlet to service the vehicles collected on it in queue). So, incorrect consideration of the phenomenon of "increase" and "decrease" of the length and range of the cumulative remaining queue (and subsequent initial queue) leads to errors in the calculation of the average maximum back-of-queue size. Under unsaturated traffic flows in the analysis of individual signalling cycles, the estimation errors of the initial queue are about 2 vehicles, while in the analysis of the 15-minute period they are slightly larger and are already about 4 vehicles. The results of mean square errors are much worse in the analyzes for saturated and oversaturated traffic flows. For analyzes with a single cycle period, errors amount to less than 15 vehicles, while for an analysis period of 15 minutes - as many as 21 vehicles. These are significant error values that can also be affected by the lane capacity calculation model (see further considerations in the summary).

The results of estimating the length of the remaining queue $Q_{OS}$ from the chosen period of analyzes testify to their fairly convergent determination in comparison with real data. Error values are in the range of up to 2 vehicles for one cycle length analyzes. However, in interval analyzes of 15 minutes in length, these errors increase and are in the range of 3 ÷ 6 vehicles. Attention is also drawn to the fact that with the help of estimators of the remaining queue in unsaturated traffic flows, a non-zero value is always calculated, which of course has an impact on small calculation errors. The exception is the Canadian method.

The author did not undertake analyzes for a sampling period of 1 hour due to the 'nature' of urban traffic and too dynamic variability in the time of demand for movement in the urban area. It is believed that the analysis period of 1 hour in urban traffic conditions is too long, in which significant fluctuations in traffic intensity are ignored. In addition, a sample of 75 hours of analysis is too small to make sufficient comparisons in statistical analyzes.

## 5. Discussion and Conclusions

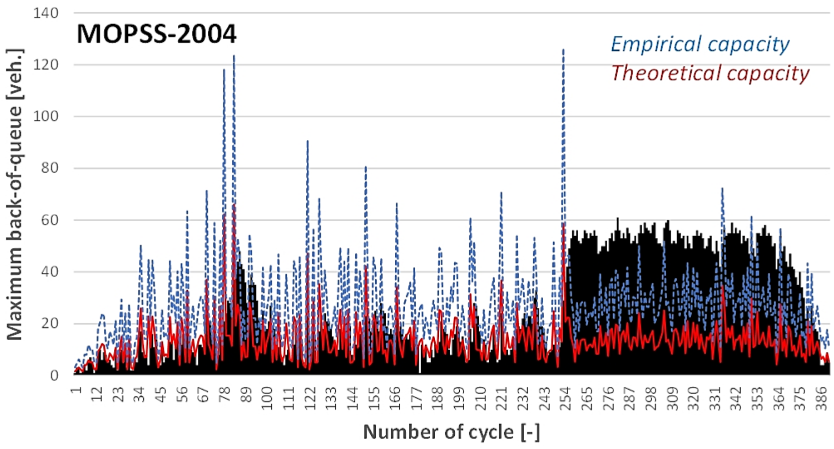
The maximum queue length determined by most methods refers to the average queue condition, which is formed as a result of arriving vehicles to intersection inlet in a red signal interval. The calculation result obtained in this way is corrected (its size is extended) by an estimate of the length of the remaining queue from the considered analysis period, due to the lack of service for all vehicles accumulating at the lane during the transmission of the green signal (or due to "random traffic fluctuations" during the analysis period). It does not determine the traffic conditions that prevailed before the selected period for analysis in most calculation methods. Therefore, it is not taken into account whether there is already a queue remaining in the period from the period preceding the period being analyzed, and therefore whether there was an overload of the intersection inlet before the analysis period. US methods only (HCM-2000 and also HCM-2010, HCM-2016) have an estimator that considers the possibility of an initial queue in the considered period of analysis.

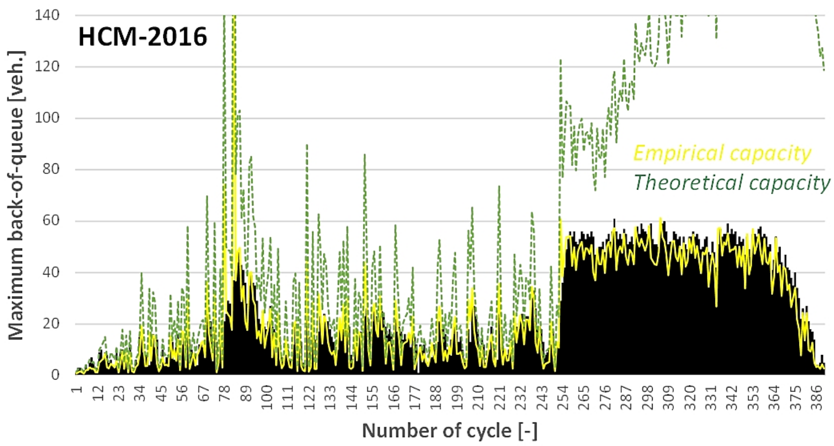
The obtained results of the maximum queue estimation errors appear to be relatively large and are at a fairly similar level. However, the important fact is that the results of calculations obtained using American methods significantly overestimate the extreme state of the vehicle queue, while the other methods give an underestimated result of this extreme state.

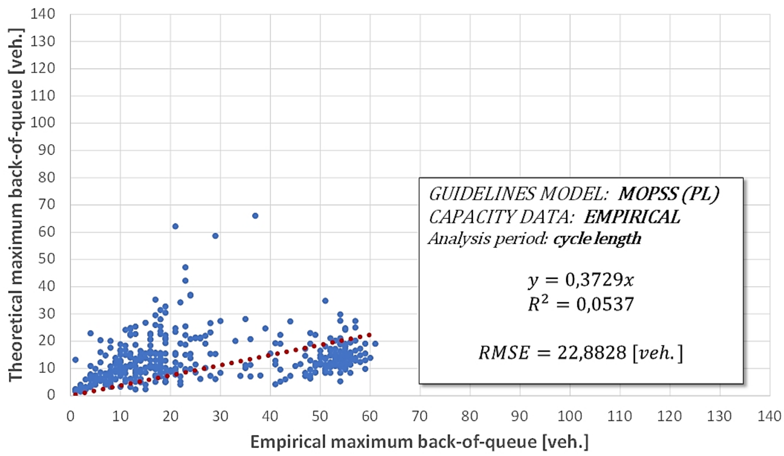
According to the comparative analysis, the maximum queue length is not determined correctly. This is particularly the case in the worst traffic conditions in cities (periods of greatest transport demand). As already emphasized, the underestimation results from the lack of an estimator of the initial queue length. However, the main overestimation errors result from the fact that the initial queue estimator depends on determining the average traffic conditions of a given period, determined in the theoretical way (using average lane capacity - i.e. saturation flow, effective green signal time and cycle length). Because of this, even a small capacity estimation error has a huge impact in determining the initial queue size. In addition, such a multiplied error in the conditions of persistent congestion (traffic oversaturation) for a long period causes an incorrect determination of the initial queue accumulation process. As consequently also subsequent sampling periods and also the queue remaining size for successive signalling cycles. Calculation errors also significantly affect the possibility of shrinking the maximum queue (reducing its range by "absorbing vehicles through the inlet" during the occurrence of capacity reserves in relation to the arrival flow intensity). As it turns out, this is of great importance when comparing theoretical and real capacity results.

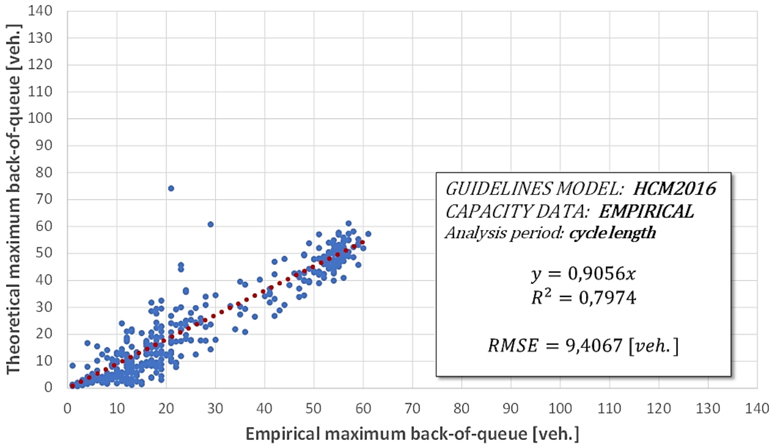
Also noteworthy is the fact that the initial queue value $Q_{IN}$ is differently included in the calculations in both HCM methods, despite specifying this queue size in the same way (difference in supply demand from the period preceding the period considered). In the HCM-2000 method, the length of this queue is included as a factor correcting the value of the remaining queue length calculation $Q_{OS}$. Whereas in the HCM-2016 (and earlier HCM-2010) method, the initial queue length estimator $Q_{IN}$ is used directly to calculate the process of changing the maximum queue length. The possibility of extending and reducing the back-of-queue size due to traffic conditions prevailing at the intersection inlet both before the analysis and in the considered period of analysis is taken into account. It should be mentioned that in addition, in the HCM method from 2000, the present length of the initial queue is also included in the calculation of the arrival flow rate $q$, which is not done in the methods since 2010.

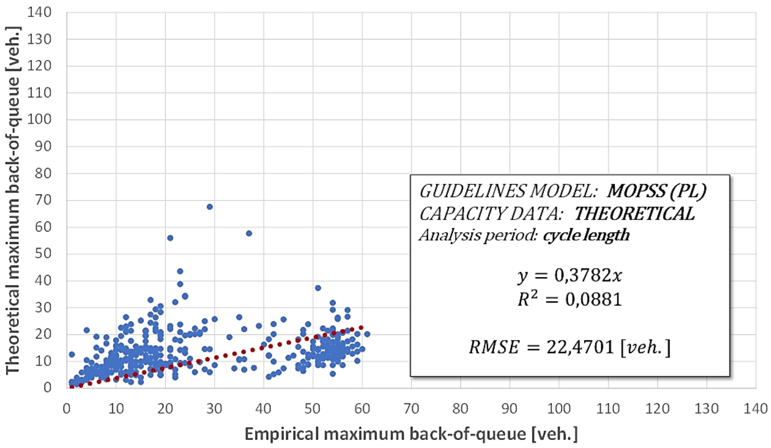
This example of incorrect estimation of the initial queue length and the impact of these errors was decided to illustrate in the charts below. Figure 6 shows the distribution of the empirical maximum queues per cycle over a period of 13 measuring hours at one of the intersections, with the results of calculations of the maximum back-of-queue sizes marked on it, taking into account the value of real and theoretical capacity (on the left by the Polish method MOPSS-2004 [5], on the right – US method HCM-2016 [13]).


MOPSS-2004
Empirical capacity
Theoretical capacity
Maximum back-of-queue [veh.]
Number of cycle [-]


HCM-2016
Empirical capacity
Theoretical capacity
Maximum back-of-queue [veh.]
Number of cycle [-]


GUIDELINES MODEL: MOPSS (PL)
CAPACITY DATA: EMPIRICAL
Analysis period: cycle length
$y = 0{,}3729x$
$R^2 = 0{,}0537$
$RMSE = 22{,}8828$ [veh.]
Theoretical maximum back-of-queue [veh.]
Empirical maximum back-of-queue [veh.]



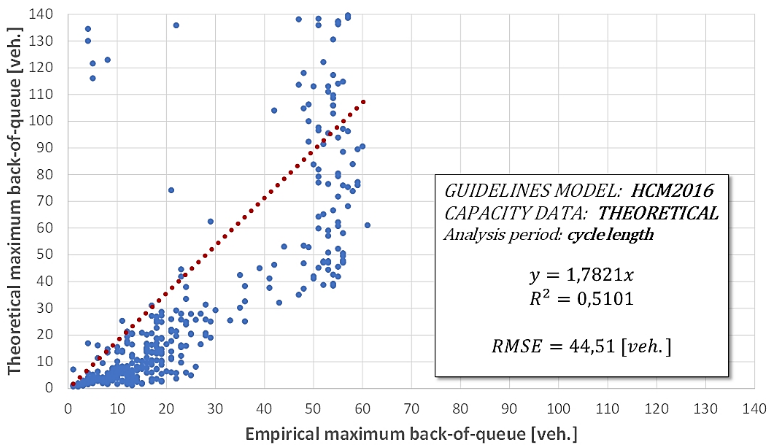




**Fig. 6. The distribution of the maximum queue length for a selected intersection with traffic lights over a period of 13 measuring hours along with an analysis of the accuracy of estimating this queue**

In addition, below these charts the results of estimation accuracy are presented on the basis of empirical and computational data comparisons - taking into account the value of real and theoretical capacity (on the left, respectively, the Polish method, and on the right, the American method). To show the essence of the error, for this example of analysis a junction was selected, at which the longest supersaturation state was observed (4 h).

By comparing the data presented in Figure 6, the following conclusions can be drawn:

- in a state of persistent blockage (permanently long oversaturation), none of the models correctly estimates the maximum back-of-queue size (calculating using theoretical capacity model);
- the American model, having an initial queue length estimator and taking into account real capacity data, gives the best approximation of the results relative to reality (value of the coefficient of determination $R^2 \approx 0{,}80$); in addition, estimating with this model in extreme conditions gives a fairly good approximation of the calculation results;
- in the case of calculations using theoretical capacity data, the HCM model significantly overestimates the extreme states of the maximum queue; in addition, in several cases duplication of estimation error and incorrect accumulation of the initial queue occur for further periods of analysis;
- the Polish model (having approximate error values to other calculation methods, except the American one), in extreme traffic conditions significantly lowers the result of the maximum queue size, whether taking into account the value of real or theoretical capacity.

The same comparative analyzes were performed for the other methods considered, for each individual intersection covered and also at different sampling intervals (5, 15, 30 and 60 minutes). In each of these cases, the conclusions listed above are identical. The analysis for the 60-minute interval is statistically doubtful due to the small sample of hourly data.

The statements contained in the article seem to confirm the author's initial supposition [14-15, 18] that the length of the initial queue should be included in the calculation of the maximum queue size. Nevertheless, taking into account the received calculation errors for extreme states, it is still necessary to search for appropriate algorithms for the correct determination of this quantity. The author's proposal in this regard will be presented in a separate article on the new proposal for modelling the maximum back-of-queue size.

In addition, it is believed that the issues collected in this study regarding vehicle queues and the results of estimation errors reflect: firstly, the complexity of the problem of vehicle queues in cities at intersections with traffic lights, and secondly - the importance of the problem raised in the context of the growing automotive congestion in urban areas, with the correct decision-making related to the planning, design and operation of traffic-controlled urban infrastructure.


## OCENA WYBRANYCH METOD SZACOWANIA MAKSYMALNYCH DŁUGOŚCI KOLEJEK POJAZDÓW NA WLOTACH SKRZYŻOWAŃ Z SYGNALIZACJĄ ŚWIETLNĄ

W artykule przedstawiono charakterystykę oraz ocenę dokładności szacowania maksymalnych długości kolejek pojazdów na skrzyżowaniach z sygnalizacją świetlną za pomocą powszechnie stosowanych na świecie metod obliczeń. Do analiz wybrano najnowsze wydania metod stosowane w: Stanach Zjednoczonych, Kanadzie, Australii, Niemczech i w Polsce.

W celu przeprowadzenia analiz dokładności wykonano badania ruchu na 5 wlotach skrzyżowań w trzech różnych miastach w Polsce (Bydgoszcz, Toruń, Warszawa), obejmujące wszystkie fazy tworzenia się i zmiany długości kolejki pojazdów w trakcie poszczególnych okresów cyklu sygnalizacyjnego. Łącznie w analizach dysponowano wynikami badań z 81 godzin obserwacji około 23 tys. kierowców pojazdów.

W wyniku przeprowadzonych analiz stwierdzono między innymi:

- nieznaczne różnice w budowie modeli matematycznych rozważanych metod obliczeniowych, z wyjątkiem modelu amerykańskiego z roku 2016,
- małe błędy szacowania długości kolejki maksymalnej w stanach nienasyconego przepływu pojazdów (~3-5 pojazdów/cykl oraz ~2-6 pojazdów/15 minut),
- dość duże błędy szacowania długości kolejki maksymalnej w stanach nasyconego i przesyconego przepływu pojazdów (~11-16 pojazdów/cykl oraz 15-18 pojazdów/15 minut),
- największy wpływ na błędy szacowania w stanach przesycenia ruchem ma nie uwzględnianie lub błędne określanie tzw. długości kolejki początkowej.


**Słowa kluczowe**: długość kolejki pojazdów, skrzyżowania z sygnalizacją świetlną, inżynieria ruchu drogowego

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