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METHOD OF OCCUPANCY-BASED TRAFFIC LIGHT PRIORITY FOR PUBLIC TRANSPORT

Summary. This paper deals with the problem of urban traffic control, considering public transport as a priority. According to the authors, the occupancy of a means of transport is one of the key decision variables in the process of prioritisation within a traffic signal program. This study aims to construct a method of occupancy-based traffic light priority for public transport and investigate the possibility of using this information to increase the efficiency of signal control for time loss. The mathematical model of the priority level conditioning procedure proposed in the method was tested using a microsimulation model of the intersection. The simulation results were collated and compared with an approach that does not consider vehicle occupancy. Under given traffic conditions, the use of the proposed method allows for reducing the average time losses per person in the modelled road network.

Keywords: traffic light control, occupancy of the vehicle, public transport, simulation approach

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1. INTRODUCTION

1.1. Transport systems in cities

The development in the field of motorisation and the increase in the wealth of the society significantly influence the transport behaviour of city residents. On the one hand, due to the process of urban sprawl, the inhabitants become more mobile. The daily commute to the workplace or university involves the necessity to travel often up to several dozen kilometres a day within the city [3, 10]. On the other hand, owning a vehicle, once considered a privilege, is now the norm for most people. Moreover, almost every adult member of a household possesses a car these days.

Consequently, a constant increase in traffic intensity in the road network is noted, causing a reduction in smooth traffic flows in cities. A manifestation of this dependence is the globalisation of the phenomenon of transport congestion, the symptoms of which are usually observed in the road network, especially in the area of intersections. Currently, the increase in traffic intensity and the adverse effects of transport congestion are often reduced by favouring journeys made by public transport (PuT). In general terms, travellers are encouraged to make their daily journeys by bus, tram or other public transport instead of private transport (PrT).

Although traffic light systems are mainly used to increase safety at intersections, when well designed, they can also improve the traffic efficiency of road users [8]. The systems offer the possibility of implementing public transport prioritisation methods in the traffic light control algorithm. This aspect constitutes the background for the considerations put forward in this article [9, 27].

1.2. State-of-the-art public transport prioritisation

The issues related to the methods of prioritising public transport are widely discussed in the literature. Presently, there are two groups of methods for prioritising these types of vehicles in the transport network (apart from general legal conditions concerning the right of way in the area of intersection), that is, facility design-based and traffic light control-based methods [5, 6, 21] (Figure 1).

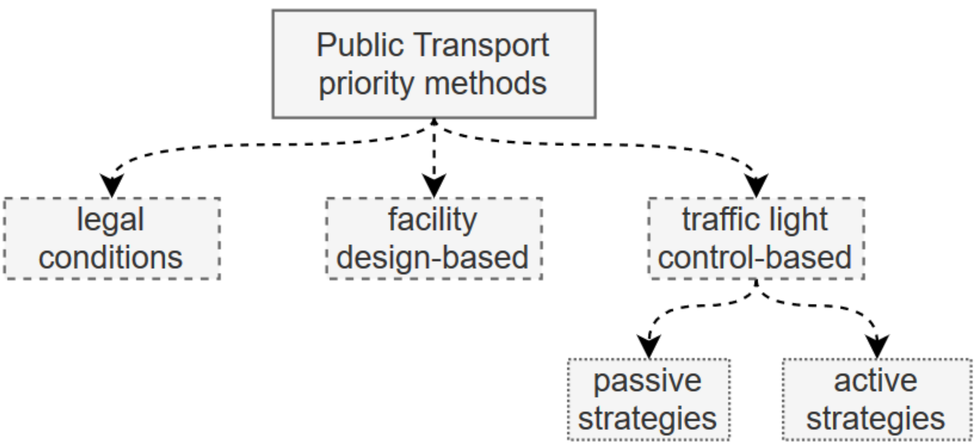

Fig. 1. Public transport priority methods classification
Source: author's work [1, 2, 6]

The first group of methods includes, among others, special roads for buses or trams separated from roads reserved for private transport or exclusive lanes for them along the streets. Also, the appearance/structure of bus stops may offer preference to this type of (public) transport. One example is a bus bulb, which ensures safety and speeds up the transfer of passengers. [5, 21].

Within the road network in contemporary cities, traffic lights play an increasingly important role regarding public transport priority. The number of traffic light-based methods developed over the years confirms this fact. Diakaki and Papamichail et al. [6] introduced an overview of 85 scientific papers and practical solutions dealing with issues of public transport priority. The time scope of the review covers the years 1969-2013. Interestingly, numerous new approaches have been presented since then.

According to the actual state of the art, traffic light-based priority for public transport can be implemented using passive or active strategies [1, 2, 22]. Passive strategies feature no need for a detection system and, consequently, an adaptive system. The traffic light system planned in this way operates on fixed time signal programs adjusted to common traffic flows and known public transport lines schedules. They are most effective when PuT vehicles run at high frequencies and when their dwell time is relatively short [21, 26]. The most important disadvantage of this approach is related to the lack of flexibility. Hence, this strategy is rarely used anymore [6, 19].

The active strategies have become an alternative to the passive ones and are now gradually replacing them. Their operation is closely related to the use of information from the system of detectors (located within the area of intersection) to adapt the signalling program to the situation at the intersection [2, 21, 26]. They prioritise specific public transport vehicles to cross the intersection by triggering special procedures in traffic light control logic. These procedures often include the following actions [2, 5, 6, 19, 20, 22]:

- generating a special priority stage after detecting a notification from a privileged vehicle (bus, tram, trolleybus). When there is no notification, the priority stage is omitted in the signal program;
- green signal extension that allows extending the duration time of the active signal stage;
- changing the sequence of signal stages realised as the shortening of the displayed active phase and the earlier display of the phase for public transport vehicles, which may include time compensation for the shortened signal stages.

Moreover, these actions can be implemented individually or in combination. The decision of which action and when has to be activated and may be made by the signal controller using a rule-based method [7, 20, 21] or optimisation [5, 11, 23]. The concept of priority levelling and the methods for assessing its effectiveness are crucial, as it is frequently argued that unconditional prioritisation may result in the deterioration of overall traffic conditions [5, 12, 20, 26]. In several studies, these decisions are made based on deviations from the schedule or order of requests of the arriving PuT vehicle [16]. It means that frequently only late vehicles are considered for priority at the signal-controlled intersections. Furthermore, in a situation where two equally delayed vehicles are waiting at the intersection, the vehicle that sent the request to the signal controller is served first.

Nowadays, many research papers indicate that more parameters need to be considered in the process of PuT vehicle's prioritisation. Hence, the following factors are commonly used [6, 7, 18, 25]:

- actual location of PuT vehicles relative to the signalised intersection [2, 7, 12, 21, 23];
- actual speed of detected PuT vehicles [2, 7, 15];
- intensity of traffic on the approaches to the signalised intersection [5, 7, 14, 26];

- number of passengers in the cabin of PuT vehicle [2, 5, 7];
- the deviations from the PuT vehicle schedule [7, 11, 12, 20, 21, 26];
- values of PuT vehicle energy consumption [4, 7, 24];
- values of PuT vehicle emissions [7];
- PuT vehicle waiting on the stop [21].

The occupancy-dependent PuT vehicle prioritisation methods are relatively new. Making the control method dependent on this parameter may determine the level of the assigned priority. Hence, it may constitute the basis for the conclusion that sometimes it is more effective for all road users not to give priority to a bus or a tram (for example, when the route ends and it is empty) or give it to other bus/tram (which is more occupied). So far, only a few studies have considered this aspect in detail.

In 2011, Christofa and Skabardonis [2] presented a traffic light control procedure that minimises the total delay per person in the network while assigning priority to transit vehicles based on their passenger occupancy. The presented approach was tested using a simulation at a signalised intersection located in Athens, Greece. The results showed that the proposed system might lead to significant reductions in PuT users' delay and the total person delay at the intersection under given conditions.

Efimenko et al. 2018 [7] presented research dealing with the issue of priority of PuT vehicles on a simple signalised 4-inlet intersection. The used method assumes delays of PuT vehicles as the main factor of prioritisation. The actual number of passengers in the vehicle constitutes an auxiliary criterion in the process of ensuring the priority of PuT vehicles. In this way, using a simulation approach, those authors formulated decision rules of the investigated traffic light controller logic. Consequently, they achieved a notable reduction in the delay of passengers travelling by public transport.

A slightly different technique assuming information about occupancy but for its average value, both for private and public transport vehicles, is presented by De Keyser et al. [5]. They compared the results obtained through the microsimulation of four different strategies of traffic light control. Based on the obtained delay data, they noted that the deterioration of general traffic conditions in the road network is caused by a higher priority for PuT vehicles. Thus, a trade-off based on the calculation of the minimal number of passengers in PuT vehicles, necessary to justify a higher level of priority, is proposed. Thus, the authors selected the best strategy depending on the actual traffic conditions in total passenger travel time (both PuT and PrT passengers).

The authors of the publications mentioned above emphasised the importance of vehicle occupancy in the traffic control process. In their opinion, strategies based on this factor are in line with the trend of increasing people's mobility.

The use of the occupancy factor in the prioritisation process also raises some criticism. In 2016, Molecki [18] noted that the direct use of the occupancy of the vehicle as one of the decision-making factors might not reflect the actual needs of passengers. Thus, there may be a situation of giving higher priority to a full vehicle ending the route rather than to an empty vehicle starting the route for which plenty of people wait at the next stop.

1.3. Objective of research

According to the author, in the current state of knowledge, there is little research focused on a thorough analysis of the impact of the vehicle occupancy aspect on the transport efficiency in the road network, especially with simultaneous consideration of parameters such as emissions, energy consumption, delays of PrT vehicles, deviation from PuT schedule and others. Previous attempts to use this parameter are limited given the adopted assumptions regarding the occupancy levels of public transport vehicles and the consequence of their usage to the traffic condition. Most importantly, virtually none of them examines the range of usability of the vehicle's occupancy factor depending on the adopted control parameters. Apart from some imperfections, the mentioned articles also contain opinions that deny the practical application of this parameter.

For this reason, these potential research gaps are the basis for conducting studies aimed at developing a comprehensive method for active prioritisation of public transport in the area of intersection. This paper is a description of pilot studies focused on this aim. The presented analyses and results are included in a thorough, multidimensional study of the impact of PuT vehicle occupancy on the control and, consequently, traffic conditions of all road users in the intersection area.

Thus, at this stage of the work, the author proposes to verify the following research conjectures:

Conjecture 1: *the occupancy of the means of transport is one of the key variables in urban traffic control strategies accounting for the prioritisation of public transport*.

Conjecture 2: *under certain conditions, the occupancy of the means of transport has a strong influence on traffic conditions for overall delays for all transport participants*.

In the following section of this paper, the subsequent steps of the proposed method are described in detail - Section 2. Section 3 presents a verification and evaluation of the method according to the microsimulation model. Finally, Section 4 contains the discussion of the obtained research results and provides conclusions for further work.

2. PROPOSED METHOD

To investigate the previously described issues and verify the specific argument mentioned before, it was decided to prepare a concise sequence of research tasks. The method presented in this section is based on the simulation approach technique, which is used to examine a set of different traffic management strategies. The method consists of five related main steps (Figure 2), and each of them is a collection of minor sub-steps.

The first step is to collect and organise all initial data necessary for further steps. These steps, among others, include the following components:

- properly scaled side plan of traffic network, which contains geometric intersection, road signs and horizontal markings. It is used as a background for both traffic modelling and traffic light design tools as well;
- traffic volumes and public transport schedules obtained by traffic surveys or received from the macroscale model;
- vehicle occupancy, acquired from own measurements or received from traffic management body (for public transport vehicles).

The step based on collecting initial data is crucial since it determines the successful validation of both the microsimulation model and the traffic light controller.

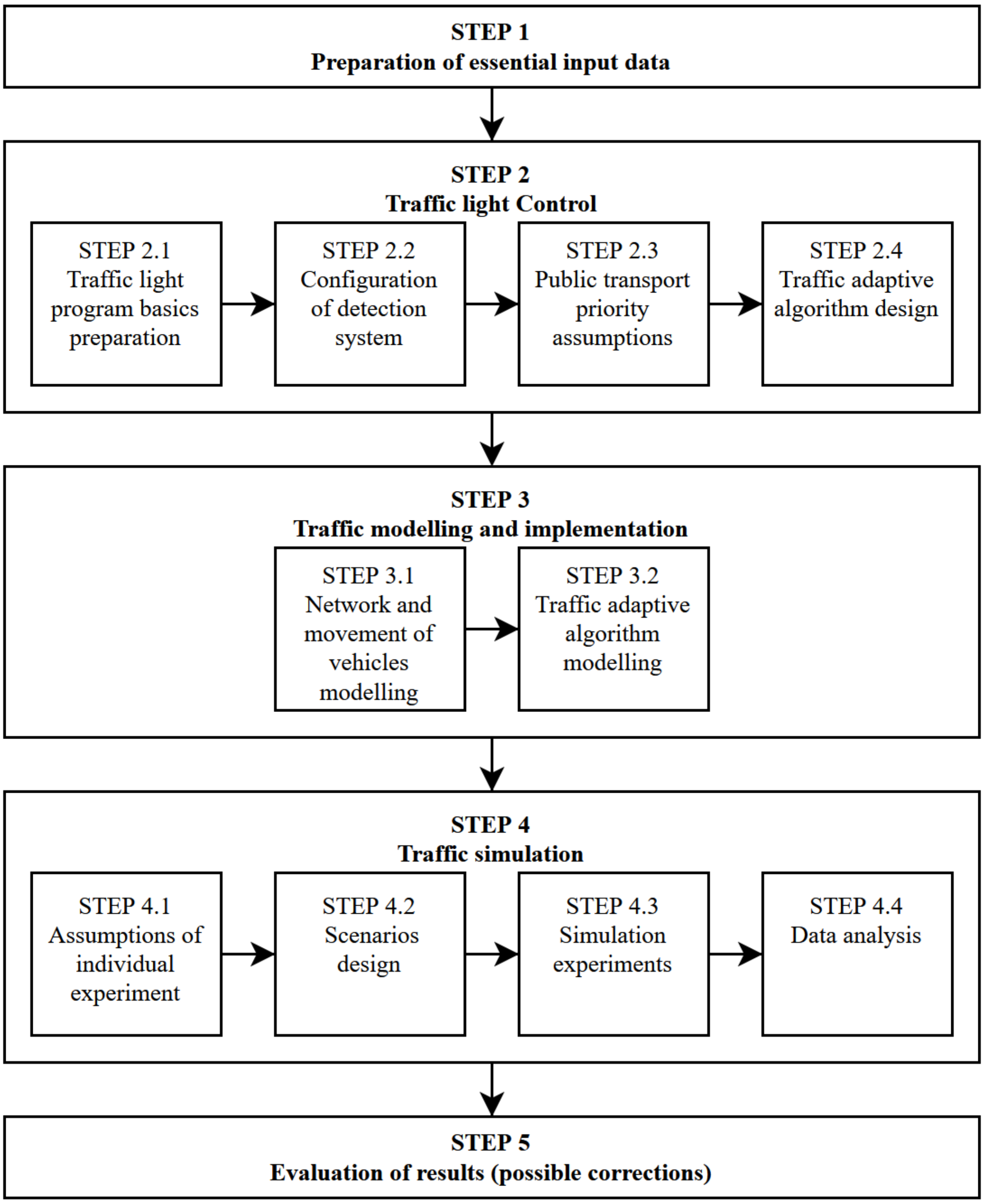

Fig. 2. Key steps of the proposed method

Based on these input data, in step 2, the process of designing a traffic light controller is undertaken. At first (Sub-step 2.1), the controller elements such as phases of signals are planned, and then intergreen times are calculated. Afterwards, non-conflicting phases are attributed to the same signal stages. Minimal t_{min} and maximal t_{max} durations of each signal stage are planned by traffic volumes and vehicle flow structure. In consequence of this step, a fixed signal program is prepared.

The signal program intersection has to be provided with an efficient detection system (Sub-step 2.2). Therefore, it is essential to plan the structure of the detectors and configure their operation. The detectors are the basis for the development of the effective structure of the control algorithm and public transport priority strategy selection.

The following sub-step 2.3 is dedicated to setting the public transport priority strategy. The proposed method assumes the occupancy of public transport vehicles as one of the key factors in the process of traffic condition improvement. Thus, every PuT vehicle is described by the following parameters:

- *number of passengers – $p_i(t)$*, which is the actual number of passengers in the *i*-vehicle,
- *vehicle occupancy level – $o_i(p_i(t))$*, which is a presentation of the actual number of passengers in the i-vehicle, as a part of a specific occupancy range; it is classified according to Formula (1):

$$o_i(p_i(t)) = \begin{cases} 1, & \text{if } v_0 \le p_i(t) \le v_1 \\ & \dots \\ K-1, & \text{if } v_{(K-2)} < p_i(t) \le v_{(K-1)} \\ K, & \text{if } v_{(K-1)} < p_i(t) \le v_K \end{cases}; \quad \forall\, i = 1,2,\dots,n;\ p_i(t) \in N \tag{1}$$

Where:

N – number of detected public transport vehicles (requesting the same priority signal stage),
i – public transport vehicle index,
t – time parameter,
$p_i(t)$ – the actual number of passengers in the *i*-vehicle,
K – number of occupancy ranges,
$v_0, v_1, v_{(K-2)}, v_{(K-1)}, v_K$ – threshold values of ranges.

- *reduction factor – $ri(o_i(p_i(t)))$*, the parameter which determines how much the current signal stage (reserved for PrT flows) can be reduced (when the demand for its extension is detected) if the priority stage call of public transport *i*-vehicle is also detected. Its value depends on the i-vehicle occupancy level $o_i(p_i)$ – a higher level of occupancy causes a lower value of reduction factor. The received factors are described as elements of a set of reduction factors X_a, Formula (2).

$$X_a = \{x_{a1}, \dots, x_{a(K-1)}, x_{aK}\};\ \forall\, a \in N \text{ and } a \le A \tag{2}$$

Where:

a – set index, $a = 1, 2, \dots, A$,
A – number of analysed reduction factor sets,
x_{aj} – value of reduction factor of *a*-set and *j*-occupancy range, $j = 1, 2, \dots, K$,
other markings as above

The value of the reduction factor is expressed by Formula (3):

$$\mathrm{r_i}\left(\mathrm{o_i}(\mathrm{p_i}(t))\right) = \begin{cases} x_{a1}, & \text{if } \mathrm{v_0} \le \mathrm{p_i}(t) \le \mathrm{v_1} \\ & \dots \\ x_{a(K-1)}, & \text{if } \mathrm{v_{(K-2)}} < \mathrm{p_i}(t) \le \mathrm{v_{(K-1)}} \\ x_{aK}, & \text{if } \mathrm{v_{(K-1)}} < \mathrm{p_i}(t) \le \mathrm{v_{(K)}} \end{cases}; \quad \forall\, i = 1,2,\dots,n;\ p_i(t) \in N \tag{3}$$

While a detection system detects more than one PuT vehicle moving in the same priority signal stage on non-collision routes, a reduction factor is enhanced. In the proposed method, the final reduction factor -$R(t)$ - stands for a product of the value of reduction factors $r_i(o_i(p_i(t)))$ for each vehicle (Formula 3).

$$R(t) = \prod_{i=1}^{n} r_i\left(o_i\big(p_i(t)\big)\right) \tag{4}$$

Eventually, in sub-step 2.4, taking the previously mentioned data and formulas into consideration, an adaptive traffic algorithm can be designed. The method presented in this paper assumes rule-based control logic. It means that in each signalling interval, several decisions (based on information received from the detection system) are made to determine the further course of the signal program.

The next part of the method assumes a modelling approach. At the beginning of sub-step 3.1, a microscopic simulation model is designed. According to the site plan, the road infrastructure elements are identified and modelled in the simulation tool. Next, the traffic generators are introduced, and priority rules at collision points and velocity limits on arcs are determined. Then sub-step 3.2 starts. It is focused on traffic control rules (designed during step 2), which are reconstructed and implemented into the simulation model.

The process of preparing and conducting the experiments is the penultimate stage of the presented method. It involves the four following sub-steps. First, the assumptions of individual experiments (as the duration of a single simulation) are introduced (sub-step 4.1). Then in 4.2, various strategies for traffic light control are arranged. The total number of scenarios L is equal to the product of the total number of sets of reduction factors A and the number of combinations of occupancy threshold ranges C, where C is the K-value combination of the M-value set, and M is not greater than maximal vehicle occupancy (*MaxVehOcc),* Formula (5).

$$L = A * C_M^K = \binom{M-1}{K-1}, 0 < K \leq M \leq MaxVehOcc \tag{5}$$

Due to the numerous combinations of occupancy ranges (For M=*MaxVehOcc*=200 and K=4, the number of combinations equals 1293699), it is recommended to account for additional assumptions limiting the size of the set. Each range's upper and lower values can be defined using Algorithm 1 below. An appropriate selection of variables makes it possible to select a representative set of scenarios dedicated to simulation experiments.

Algorithm 1.

$c = 1$ // Initialise c-iterator's first index
For $l_1 = 0$ **to** N **Step** = $step_1$ **Do**
…
For $l_{(K-1)} = 0$ **to** N **Step** = $step_{(K-1)}$ **Do**
For $l_K = 0$ **to** N **Step** = $step_K$ **Do**
If ($l_1 + \ldots + l_{(K-1)} + l_K = N$) **and** ($l_1, \ldots, l_{(K-1)}, l_K \geq MinRangeSize$) **Then**
$v_0 = MinVehOcc$

$v_1 = l_1 * MaxVehOcc / N$
...
$v_{(K-1)} = (l_1 + \ldots + l_{(K-2)} + l_{(K-1)}) * MaxVehOcc / N$
$v_k = (l_1 + \ldots + l_{(K-2)} + l_{(K-1)} + l_K) * MaxVehOcc / N$
$c = c+1$ // Incrementing c-iterator by the value of 1
End For
End For
…
End For
C = c //Execute after last "for" loop. Assign the last value of "c" to "C".

Where:

$l_{1,(K-1),K}$	–	auxiliary variable acting as iteration counters,
$step_{1,(K-1),K}$	–	the value of iteration step,
$MinRangeSize$	–	minimal size of range ($0 < MinRangeSize \leq 100$) [%],
$MaxVehOcc$	–	maximal vehicle occupancy [pers.],
$MinVehOcc$	–	minimal vehicle occupancy [pers.],
c	–	the combination of occupancy ranges counter,
C	–	the number of combinations of occupancy ranges,
N	–	the auxiliary variable.

After that, a complete collection of scenarios is subjected to the main simulation experiments (sub-step 4.3). Afterwards, all evaluation data of each simulation are analysed (sub-step 4.4). These data include, among others:

- queue length on intersection inlets,
- delays (per vehicle or/and per person),
- emissions of harmful compounds to the atmosphere,
- energy (electricity and fuel) consumption (per vehicle and per network),
- the velocity of vehicles,
- deviations from the public transport schedule.

Eventually, in step 5, the traffic light control system based on the analysed data proceeds. After that, if necessary, any corrections can be introduced, and the simulation process has to be run again.

3. VERIFICATION OF METHOD

3.1. General assumptions

The verification of the method for the presented specific objective was carried out on a microsimulation model of a fictitious isolated tramway crossing (Figure 3). In a work related to traffic modelling, the author used the PTV VISSIM tool. In the part devoted to the issues of designing the operation of signalling systems, the LISA+ tool was used.

In step 1, the author adopted specific input data values to obtain relevant traffic conditions. The basic assumptions include:

- the public transport system is represented by the tram system, which is characterised by isolated track routes;
- low intersection complexity is established, at this stage of the study, to reduce the number of disturbances that needlessly complicate the public transport prioritisation method. Thus, public transport stops and pedestrian crossings were not included in the model;
- constant high intensity of individual transport (2700 veh./h per direction) – introduced to ensure a high impact of the type (level) of public transport priority to individual transport traffic conditions;
- random distribution of vehicle occupancy, assuming an even distribution of the modal split between public transport and individual transport (Figure 4);
- a fixed tram timetable to analyse single as well as multiple tram requests (multiple requests from queuing trams) (Figure 5).

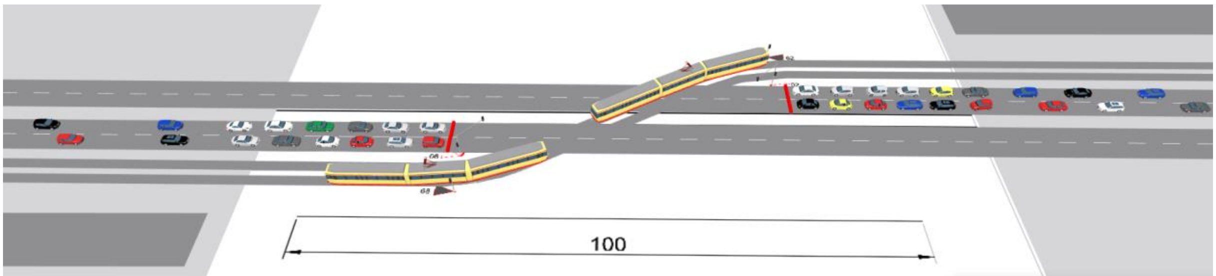

Fig. 3. View of the microsimulation model

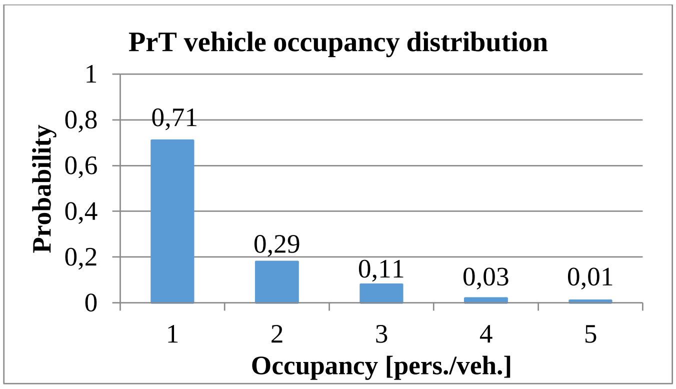

Fig. 4. Private transport vehicle occupancy distribution

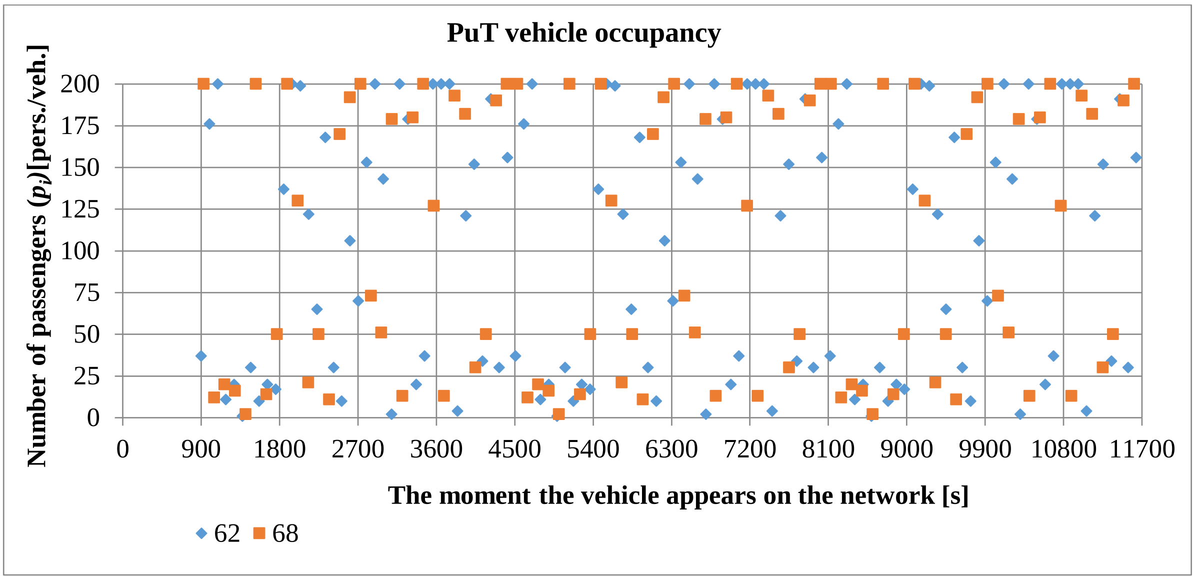

Fig. 5. Public transport vehicle occupancy – schedule

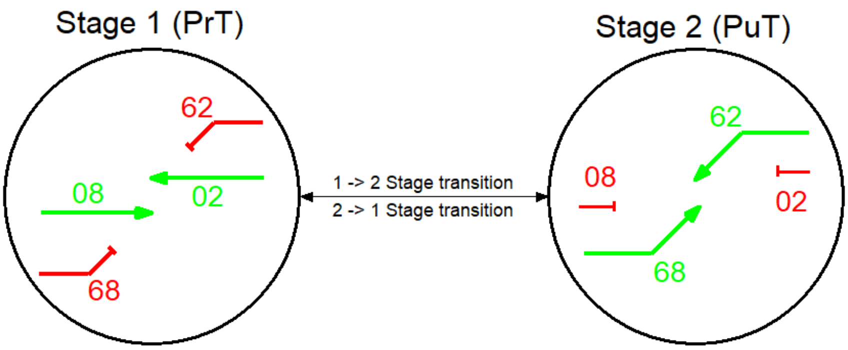

Fig. 6. Signal phases and stages

In the following step 2, the tasks focused on the traffic light program are realised. First, signal phases (signal groups) are created (02, 08, 62, 68) and assigned to the existing traffic flows. Second, the signal phases are grouped into two signal stages (1, 2), as presented in Figure 6. Then, the minimal t_{min} and the maximal t_{max} times for each stage are defined as follows (Table 1).

Tab. 1

Time characteristics of signal stages

Phase	Mode of transport	Stage	Duration of the stage	
			t_{min} [s]	t_{max} [s]
02	Private	1	5	$60/\infty^{*}$
08				
62	Public	2	5	12
68				

* If no call to stage 2 is detected, then stage 1 remains indefinitely

Subsequently, localisations of the detectors are planned, and their operations are programmed. For detecting the requests from private transport vehicles, standard induction loops are introduced. In the case of trams, the author choose a method based on radio transmitters. Because of their application in combination with the localisation data, the information about occupancy volume is also transmitted to the traffic light controller (sub-step 2.2).

According to sub-step 2.3, the number of occupancy ranges K and the number of analysed reduction factor sets A are planned. In consequence, the values of each factor are proposed. To investigate the presented case study, the values from Table 2 are assumed.

Eventually, in step 2.4, a traffic-actuated, acyclic program for traffic lights is designed for the presented road intersection (Figure 7). Stage 1 is a default stage; thus, it is activated if the detection system does not receive requests for other induced stages. Stage 2 is induced.

Tab. 2

Adopted sets of reduction factors, for K=4, A=8

		Set of reduction factors X_a								Occupancy range
		X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	
i-vehicle reduction factor $r_i(o_i(p_i(t)))$ value x_{aj}	x_{a1}	0.80	0.60	0.70	1.00	0.84	0.65	0.55	0.63	1
	x_{a2}	0.65	0.50	0.60	0.70	0.66	0.50	0.50	0.60	2
	x_{a3}	0.45	0.40	0.50	0.32	0.33	0.35	0.45	0.57	3
	x_{a4}	0.30	0.30	0.40	0.16	0.12	0.16	0.40	0.53	4

The control algorithm works according to the following principles:

- Stage 1 is always activated for at least the minimum time – $t_{min(1)}$; after reaching it, the controller checks whether there are requests for Stage 2. If not, then Stage 1 time counter – TCounter$_1$, is stopped at the value of $t_{min(1)}$;
- The detection of a request from a public transport vehicle(s) causes the resumption of Stage 1 time computation and checking of the occupancy level of the reporting vehicle(s);
- If no extension reports to Stage 1 are detected, the transition to Stage 2 is immediate.

Otherwise, Stage 1 may be extended up to a maximum time – $t'_{max(1)}$, which is equal to the product of the value $t_{max}(1)$ and the reduction factor $R(t)$

$$t'_{\max(1)} = t_{\max(1)} * R(t) \tag{6}$$

Upon reaching it by TCounter$_1$, transition to Stage 2 is activated;

- Stage 2 is always switched on at least the minimum time – $t_{min(2)}$. After reaching it by TCounter$_2$, the controller notices the presence of extension requests. Stage 2 may be extended up to a maximum of $t_{max(2)}$. After this time is exceeded, the controller proceeds with the transition to Stage 1.

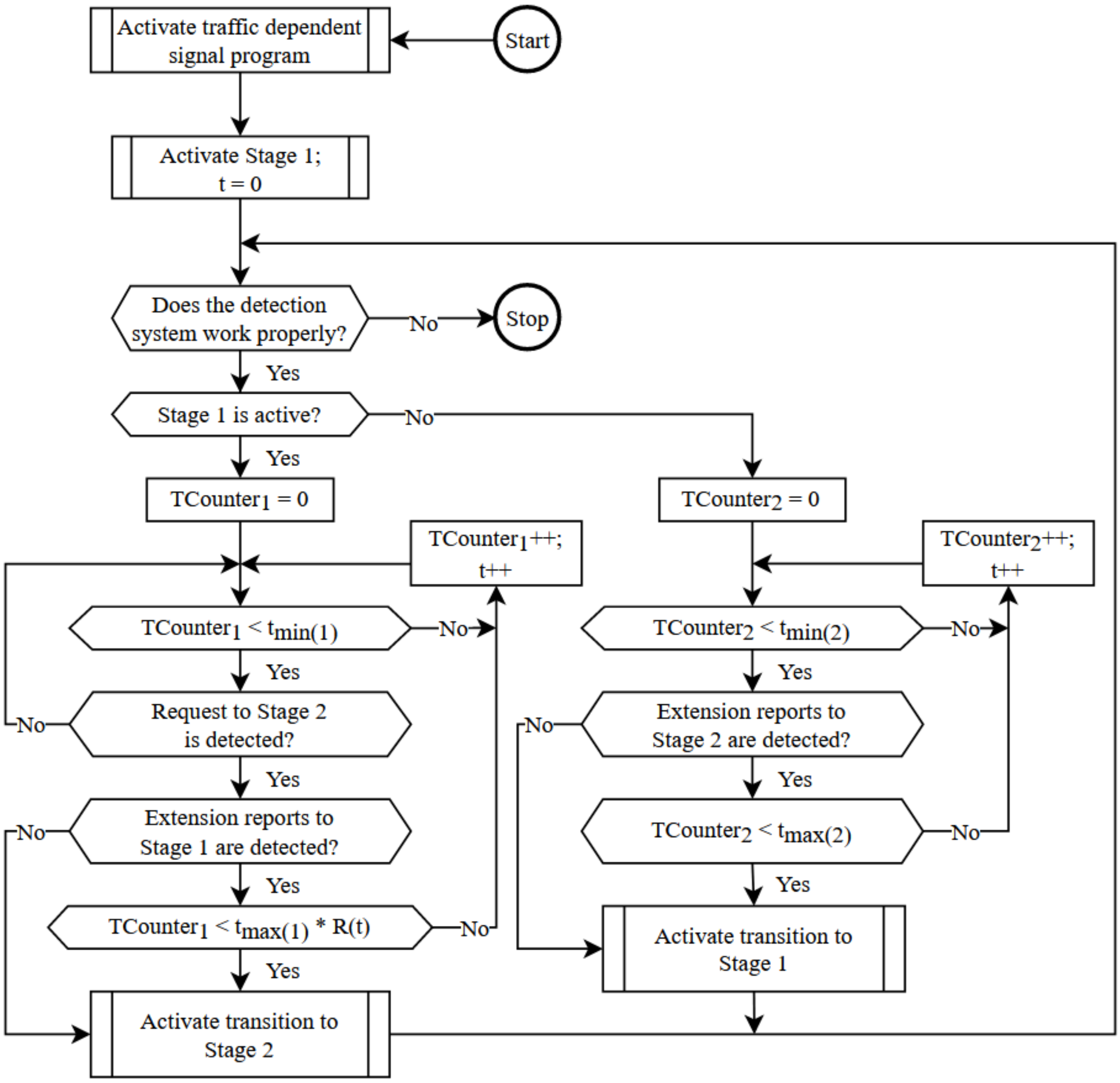

Fig. 7. Traffic light control flowchart

3.2. Microsimulation experiments

After completing the actions included in Step 3, the author considers the microsimulation modelling. A final model (Figure 8), based on common practices in that traffic modelling approach, is built. The construction of the model in the Vissim program is completed with the implementation of the traffic light system constructed in the LISA+ tool. Eventually, the model is used in a series of simulation experiments (Step 4).

Every single simulation experiment lasts 11700 seconds. Each of these experiments is divided into three phases: the warm-up, the main part and the cool-down. During the warm-up period, in 900 seconds, the network is filled with vehicles to get stabilised conditions required for further analysis. The successive stage - the main part of the experiment lasts 3600 seconds. All vehicle movement data generated in this time interval are evaluated and collected for detailed analysis. The last stage is the longest (7200 seconds) to ensure that every vehicle from the previous stage finishes its route and leaves the network. The vehicles generated in the first and last stages are not considered in the analysis of the simulation results. According to Formula

3, and the assumptions from Table 2 (K = 4), a set of examination scenarios is created. To collect the final set, Algorithm 1 proceeds with some more assumptions:

- $step_1$. $step_2$. $step_3$. $step_4$ = 1,
- *MinRangeSize* = 10,
- *MinVehOcc* = 0 (except driver),
- *MaxVehOcc* = 200 (assumed maximum of tram occupancy),
- N = 10.

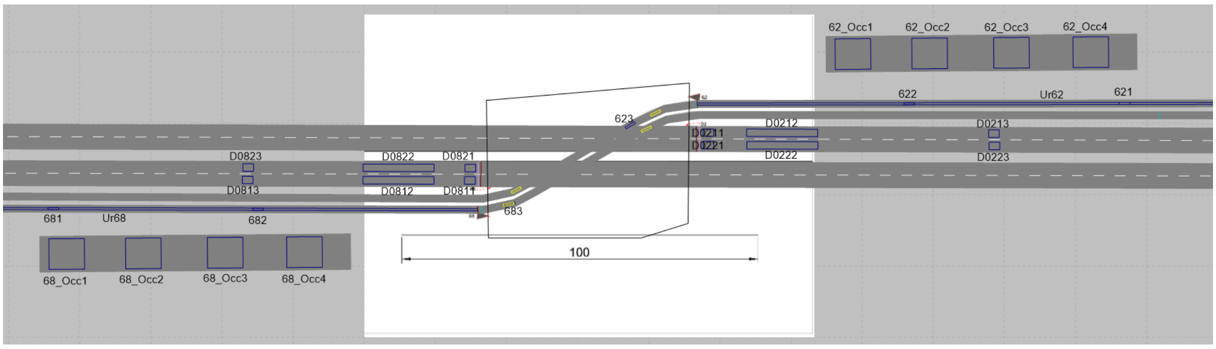

Fig. 8. Structure of the microsimulation model

Due to these assumptions, the number of thresholds values combinations of four occupancy ranges is reduced to $C_M^K = \binom{M-1}{K-1} = \binom{10-1}{4-1}$, which equals 84. Figure 9 presents all 84 combinations accepted for the analysis.

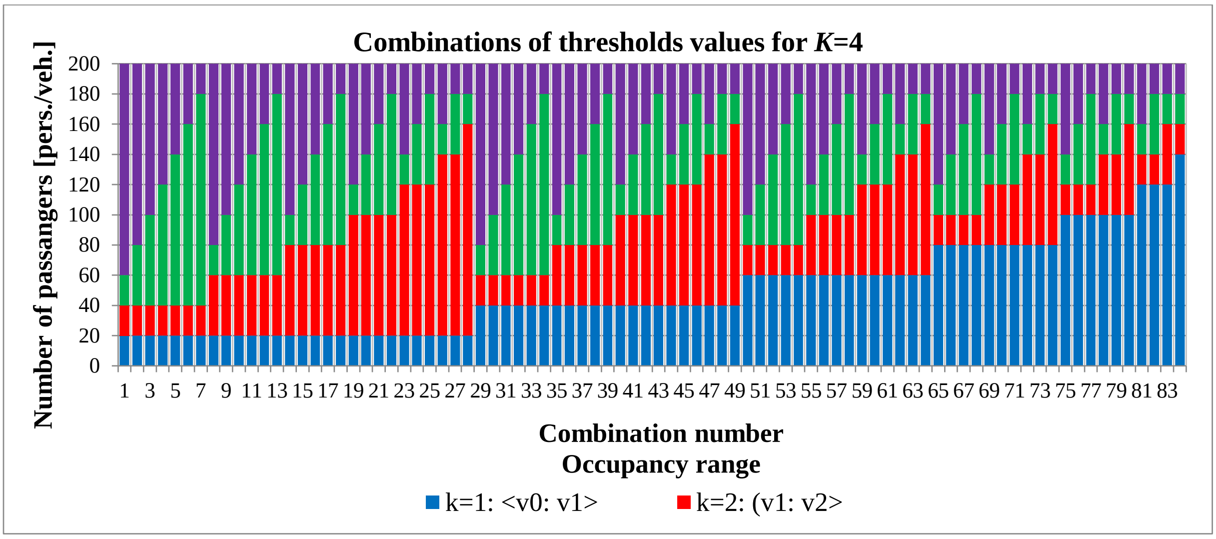

Fig. 9. Obtained combinations of thresholds values of occupancy ranges

In consequence, the total number of scenarios L based on Formula (5) is 8 * 84 = 672.

Furthermore, the author conducted additional experiments for comparative purposes to the variants resulting from the presented method. In this case, after detecting a request to Stage 2, the traffic controller always assumes the same predetermined value of reduction factor $r_i(o_i(p_i(t)))$ to each PuT vehicle regardless of the actual occupancy.

The assumed value of the $r_i(o_i(p_i(t)))$ factor ranges from 1 to 0.08 with a gradation equal to 0.02 per each next experiment, as it is presented in Figure 10. Thus, additional 47 experiments are analysed.

Due to the high number of experiments in further analysis, the author assumes the following indication:

- $Sim(1)_c^a$ – in case of traffic light control is based on the real vehicle occupancy factor (a = 1, 2, …, 8; c = 1, 2, …, 84);
- $Sim(2)_b$ – in another case, where traffic light control is independent of vehicle occupancy, where b stands for the experiment number, and the value of reduction factor is taken from Figure 9 (b= 1, 2, …, 47).

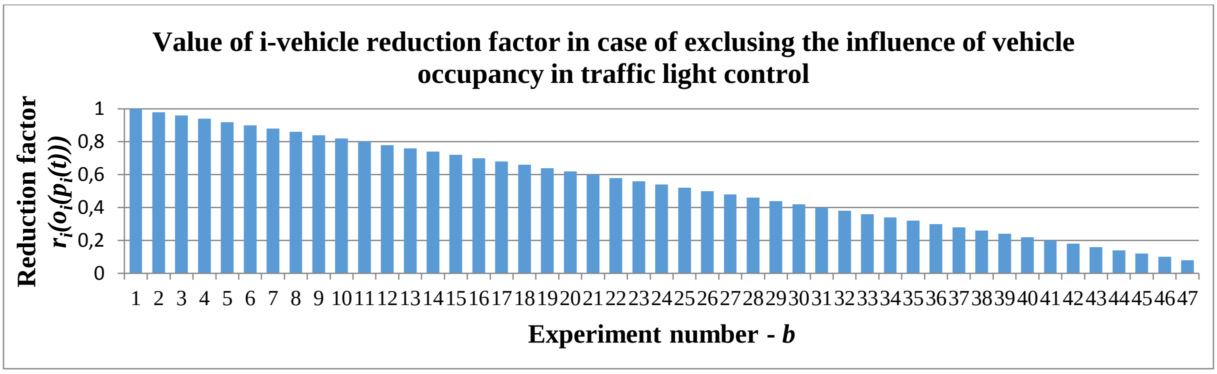

Fig. 10. The relationship between the simulation number and the value of the reduction factor in the case of comparative simulation variants

3.3. Results of the simulations

After conducting a series of simulation experiments and analysing traffic condition data, the evaluation follows. At this step, vehicle and passenger time losses are considered as only evaluation data.

The proposed method assumes the occupancy of vehicles as a decisive factor in the traffic control process. Therefore, the initial assessment and selection of the results are made based on the average delays per person in the network. Consequently, the values of delays from experiments based on the proposed method $Sim(1)_{1-84}^{1-8}$ and the values of the comparative ones $Sim(2)_{1-47,}$ are presented in Table 3. Due to the multitude of tested cases, only the most relevant results are listed there.

In those experiments where traffic control is independent of vehicle occupancy, the best score equals 19.05 [s/pass.]. It is obtained for variant $Sim(2)_{21}$. During this experiment, the reduction factor for each PuT vehicle has a constant value of 0.6. This experiment is established as a reference variant for the other ones that are based on the tested method.

In Table 3, the minimal delay for each of the analysed set of shortening factor X_a is underlined. For most of them, that is, for the series (of delay values) where a = 1, 2, 3, 6, 7, 8, the delays are higher than the reference variant. The results obtained from simulations where a = 4, 5, tend to be opposite to the reference variant. Three variants from the first series a=4 and as many as 11 from the second one (a = 5) represent a more efficient solution than variant $Sim(2)_{21}$. They are boldly marked in Table 3. The minimal, and the best, value equals 18.64 [s/pers.]. It is achieved by three alternatives from the same set, where a=5. This applies precisely to variants: $Sim(1)_{38}^5$, $Sim(1)_{42}^5$, $Sim(1)_{45}^5$. It means that under given initial conditions, the application of the presented method using the variants mentioned above results in a 2% improvement in traffic conditions from a single traveller's perspective in the network compared to the best variant of the reference approach. Thus, the advantage is much more significant concerning the other comparative variants tested. Almost half of them are improved by at least 50%.

An important factor in the interpretation of the results from Table 3 is the analysis of the coefficient of variation CV defined as the ratio of the standard deviation σ to the mean value μ. It is used to define how much the proper selection of the combination of occupancy intervals c impacts the final result of the experiment depending on the adopted set of reduction factors X_a. Actually, the lowest value of the coefficient of variation is noted in the series of delay values where a=8. In this case, it happens due to minimal differences between the successive values of the reduction factors, concentrated around the value of 0.6, which is similar to the reference variant. The highest value among all analysed results is obtained for the series of comparative variants $Sim(2)_{1-47}$ and equals CV=0.46. This results from testing a very wide range of values of the shortening factor, including the extreme values (its value ranges from 1 to 0.08 with the gradation of 0.02 per experiment). Furthermore, the highest value among the variants based only on the tested method is achieved by the variants from the set where a = 4, 5. Thus, this applies to those series of experiments for which the best results for the average time delays per person were achieved in several cases. This means that obtaining better results (using this method) is closely related to the appropriate choice of input parameters.

Tab. 3

Obtained results of average delays per person in a traffic network.

Average delay in the transport network - per person [s/pers.]											
$Sim(1)_c^a$										$Sim(2)_b$	
c \ a	1	2	3	4	5	6	7	8		b	-
1	32.81	37.43	23.33	31.07	34.62	38.86	32.68	20.51		1	31.28
2	27.88	35.67	21.97	32.23	35.70	39.08	32.39	20.31		2	30.11
…										3	29.04
16	20.31	24.80	21.05	19.65	19.70	29.03	24.12	19.77		4	28.16
17	20.10	23.22	21.70	19.20	**18.95**	25.32	24.71	19.64		5	26.87
18	19.90	24.58	19.70	**18.96**	19.95	28.33	24.17	19.17		6	26.12
19	20.19	24.72	20.84	19.41	19.39	28.78	24.02	20.22		7	25.28
20	20.31	24.80	21.05	19.65	19.70	29.03	24.12	19.77		8	24.73
21	20.10	23.22	21.70	19.20	**18.95**	25.32	24.71	19.64		9	24.01
22	19.90	24.58	19.70	**18.96**	19.95	28.33	24.17	19.17		10	23.12
23	20.45	24.72	20.93	20.05	19.70	29.03	24.10	19.80		11	23.03
24	19.84	23.97	21.26	**18.94**	18.95	25.32	24.83	19.71		12	22.84
25	19.97	24.08	19.50	18.96	19.95	28.33	24.19	19.12		13	22.45
…										14	21.90
37	20.60	25.61	20.89	20.27	19.45	29.57	23.58	19.74		15	21.69
38	20.25	24.39	21.69	19.72	**18.64**	25.86	23.86	19.64		16	21.40
39	20.13	21.03	20.39	19.82	21.06	22.70	21.70	19.20		17	20.97
40	20.41	25.50	20.66	20.00	19.10	29.31	23.27	20.19		18	20.85
41	20.60	25.61	20.89	20.27	19.45	29.57	23.58	19.74		19	20.16

42	20.25	24.39	21.69	19.72	**18.64**	25.86	23.86	19.64		20	19.96
43	20.13	21.03	20.39	19.82	21.06	22.70	21.70	19.20		21	19.05
44	20.34	25.25	21.01	20.77	19.45	29.57	24.49	19.78		22	19.40
45	20.06	23.40	21.53	19.85	**18.64**	25.86	24.56	19.73		23	19.77
46	20.90	20.94	20.04	19.72	21.06	22.70	21.44	19.24		24	19.19
…										25	20.37
52	20.62	24.84	20.93	21.03	19.70	28.75	23.74	19.74		26	19.48
53	20.39	23.85	21.73	20.09	**18.82**	23.89	23.58	19.65		27	24.24
54	20.27	20.83	20.44	20.37	21.30	21.75	21.77	19.21		28	24.89
55	20.51	24.60	20.71	20.75	19.31	28.48	23.65	20.19		29	29.36
56	20.62	24.84	20.93	21.03	19.70	28.75	23.74	19.74		30	32.82
57	20.39	23.85	21.73	20.09	**18.82**	23.89	23.58	19.65		31	31.03
58	20.27	20.83	20.44	20.37	21.30	21.75	21.77	19.21		32	31.73
59	20.31	24.68	21.06	21.55	19.70	28.75	23.94	19.79		33	35.38
60	20.20	23.36	21.59	20.23	**18.82**	23.89	25.14	19.74		34	40.38
…										35	39.38
66	20.66	23.70	20.93	21.16	19.62	22.13	23.70	19.74		36	43.44
67	20.91	22.60	21.43	20.13	**18.90**	21.83	23.88	19.65		37	45.23
68	20.86	20.69	20.18	20.89	21.38	21.04	21.47	19.21		38	45.63
69	20.36	23.24	21.06	21.23	19.62	22.13	24.37	19.79		39	43.29
70	20.49	22.11	21.86	20.39	**18.90**	21.83	23.90	19.74		40	42.55
71	20.98	20.87	20.04	20.55	21.38	21.04	22.17	19.25		41	49.61
72	21.03	22.29	22.23	20.52	19.58	22.26	24.05	19.87		42	50.51
…										43	52.40
75	20.36	23.24	21.06	21.23	19.62	22.13	24.37	19.79		44	53.01
76	20.49	22.11	21.86	20.39	**18.90**	21.83	23.90	19.74		45	53.88
77	20.98	20.87	20.04	20.55	21.38	21.04	22.17	19.25		46	81.35
…										47	81.35
81	19.61	21.57	21.59	20.57	19.69	22.85	24.54	19.80		-	-
82	21.58	20.79	20.59	20.52	21.85	21.46	22.14	19.37		-	-
83	21.46	20.22	20.51	19.88	21.36	21.85	22.02	19.41		-	-
84	21.34	20.47	20.25	19.83	20.56	21.91	22.17	19.60		-	-

Minimal value	19.61	20.22	19.50	**18.94**	**18.64**	21.04	21.44	19.12		-	19.05
μ	21.62	25.12	21.00	22.84	23.14	27.62	24.64	19.70		-	32.61
σ	2.30	4.33	0.80	5.17	5.99	5.69	2.76	0.36		-	14.89
CV	0.11	0.17	0.04	0.23	0.26	0.21	0.11	0.02		-	0.46

As the next step of the evaluation, process passenger delay analysis for the modal split is conducted. Figures 11 and 12 represent the results received in this approach. The variants mentioned above as better than $Sim(2)_{21}$ are marked as blue crosses against the background of other variants in Figure 11.

It is noteworthy as every improvement of the average delay in the network is strongly related to a high level of priority for public transport. It does not mean that all scenarios based on the proposed method improve the traffic conditions, which is shown in Figure 12. Moreover, in all variants marked as better than the comparative variant, there is a very similar proportion between the time losses for journeys made by PuT and PrT. For PrT, the delay is between 27 and 30 [s/pers.], and for PrT, is between 7.85 and 10.81 [s/pers.].

The comparative variant $Sim(2)_{21}$ is characterised by a balance between delays of both types of modal split. The reason is probably related to the balance in the division of transport tasks in the examined case.

Ultimately, the delay for public transport (PuT) vehicles is analysed in Figure 13. In this part of the study, the results obtained from experiments $Sim(1)^5_{38}$, $Sim(1)^5_{42}$, $Sim(1)^5_{45}$, representing the best results for delay per person in the network, are confronted with the reference experiment $Sim(2)_{21}$.

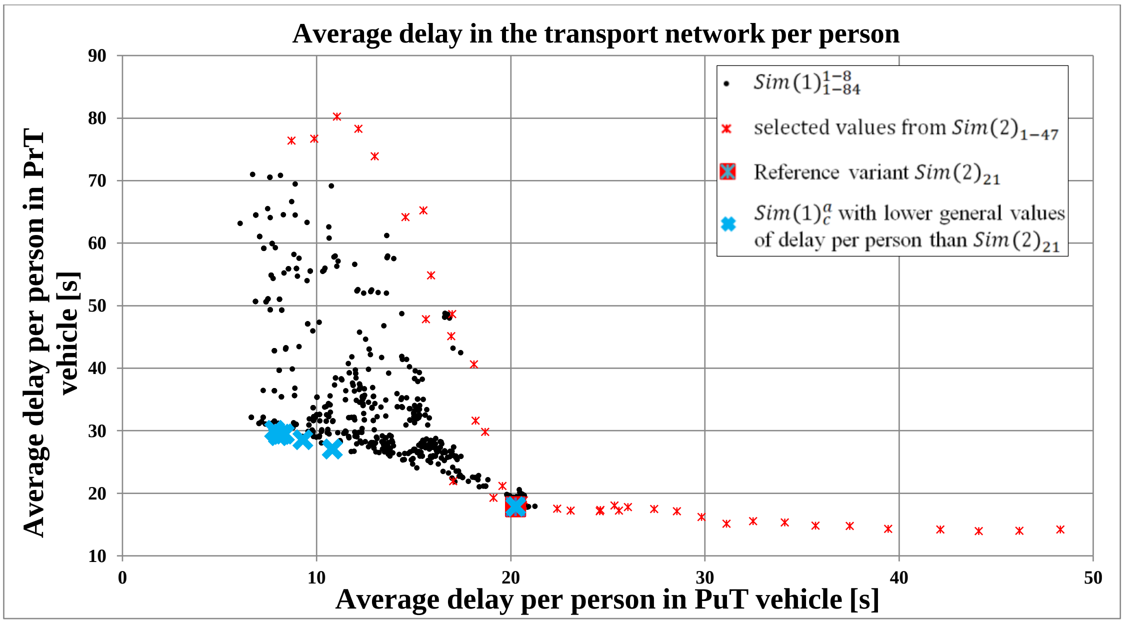

Fig. 11. Delay per person for the modal split

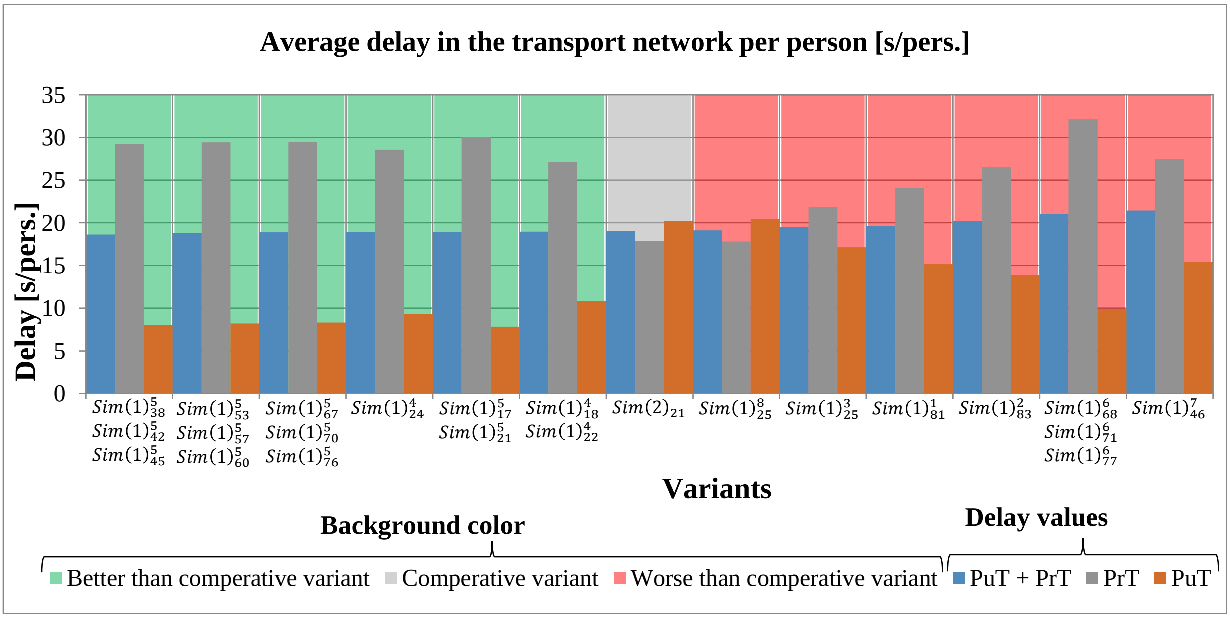

Fig. 12. Delay per person for the modal split

In Figure 13, the dependence of the delay splits into seven intervals of the number of vehicles in a given simulation experiment is shown. The obtained results show that the three variants based on the proposed method ensure the possibility of faster travel (delay per vehicle is less than 10 seconds) for more vehicles than in the case of the reference variant.

Additionally, Figure 14 relates these conclusions to the number of people travelling in the simulated transport network. More than twice as many people travel with a delay <10 seconds, and approximately five times fewer people travel with a delay of over 30 seconds for the recommended variants compared to reference variant $Sim(2)_{21}$.

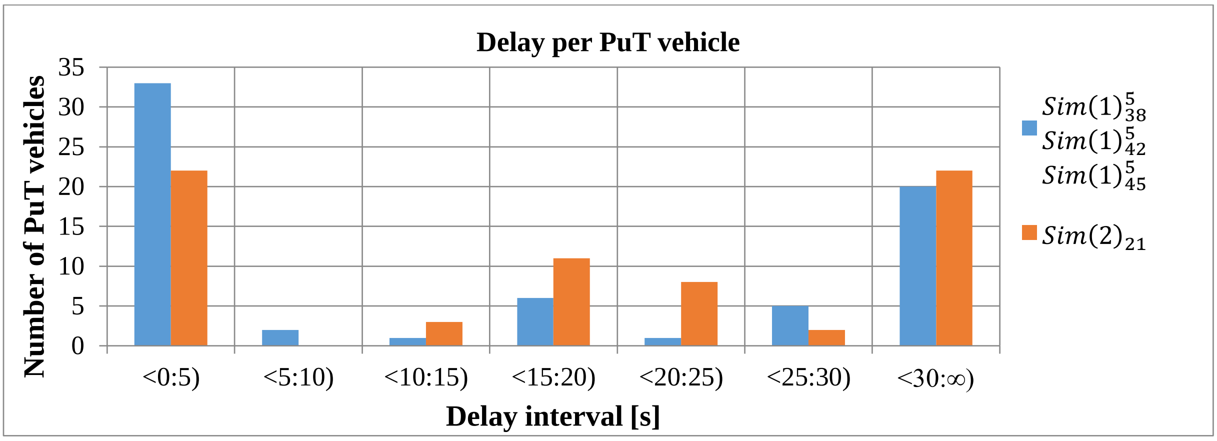

Fig. 13. Delay per PuT vehicle

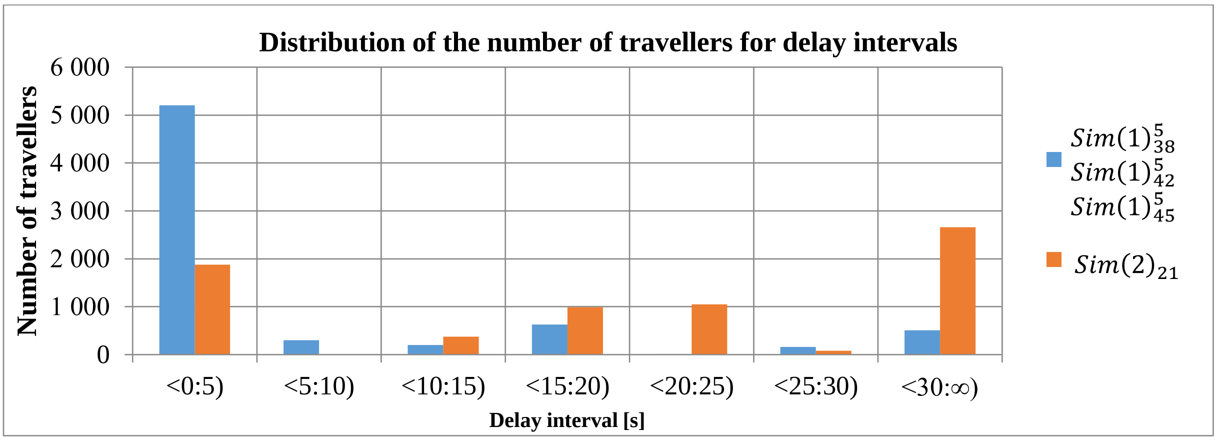

Fig. 14. Distribution of the number of travellers for delay intervals

4. CONCLUSIONS

The traffic light control method presented in this article assumes the dependence of the priority level for a public transport vehicle on its current occupancy status. The method was tested at a simple intersection in the form of a tram line and road crossing.

Under given traffic conditions, the use of the method allows reducing the average time losses per person in the modelled road network. This parameter is reduced by 2% compared to the most efficient variant that does not use the vehicle occupancy parameter, that is, independent of the occupancy ratio. It was reached while maintaining the priority of public transport over individual transport.

The experiment presented in this article constitutes a pilot study focused on one of the author's research areas. This study aimed to check whether traffic control using information about the occupancy of public transport vehicles might contribute, in given initial conditions, to the improvement of traffic.

The conducted calculations based on data obtained from the simulation approach confirm the above method. The use of information regarding vehicle occupancy and appropriate boundary conditions significantly affects the efficiency of road traffic and should be considered in further research processes.

The influence of a given type of intersection on the achieved results is worth noting. In the case of a tram crossing intersection, each trip of a public transport vehicle causes only losses for individual transport. For junctions with a more complex geometric layout and control system, the priority phase may allow vehicles to move in a conflict-free manner unless such conflict is permitted, given the public transport vehicle routes.

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