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MINIMIZATION OF PUBLIC TRANSPORT DELAYS AT ARTERIAL STREETS WITH COORDINATED MOTION

Summary. *Research results, using which the method of minimization of public transport delay is improved at intersections with the system of coordinated motion control, are given in this paper. Such transport research was carried out with simultaneous application of field measurements of the study of traffic flow indicators and computer simulation in PTV VISSIM to check the level of efficiency of coordinated control and the reliability of the results. The essence of the method is that it reduces the delay in traffic per user of the transport system during his movement through a signalized section of the road network. The effectiveness of this method is achieved under condition of significant intensity of public transport, which is provided with spatial priority in the form of the allocated lane. Invariability of the number of lanes in the area where coordination takes place, and a high level of transit (above 70 %) of straight traffic flows are compulsory indicators and parameters. The result is achieved with such phases in the direction of coordinated control, the share of the permissive signal in which is more than 45 % of the cycle duration with a duration limit of 90–125 s. With such parameters, the starting delays of the general traffic flow at the stop-lines are minimized, and the maximum values of the saturation flow are achieved. In addition, a sufficient width of the time lane is established for the passage of signalized areas by public transport. There is still some delay in public transport in such a control system, but it is connected with delays at bus stops. The introduction of such systems of coordinated traffic control is recommended on the arterial streets of citywide importance of controlled motion with a distance between adjacent stop-lines of not more than 800 m. This restriction allows avoiding the dissipation of groups of vehicles*

Keywords: *coordinated traffic control, fixed-time program control, arterial steer, transport research, traffic flow, public transport, traffic light cycle duration, simulation modeling, traffic intensity, traffic flow composition.*

1. INTRODUCTION

In recent decades, there has been a rapid development of large cities associated with the urbanization processes of individual regions. It is characterized by rapid housing construction, increasing population mobility, and its motorization level. All this has led to an increase in traffic intensity on the road network. At the same time, the network itself is developing at a much slower pace and does not meet all the travel demands. Such an imbalance between demand (traffic intensity) and supply (capacity) causes congestion of the urban road network, creating significant delays in traffic flow. Considering that the city is limited by the size of the territory, cannot infinitely increase in area, and constantly builds new streets, it is difficult to disperse intensive traffic flows in time and space. In addition, the constant construction of new transport infrastructure entails high economic costs in the current and future periods, which are associated with the maintenance of this network. Simultaneous application of all these factors stimulated the development of intelligent transport systems, which allow not only to ensure the movement of high-intensity flows of its members but also the operational management of these flows. In addition, the urban transport system should provide convenient communication between all transport districts, which requires efficient public transport operation during the transportation of a large number of passengers, especially during peak periods. Quite a small share of large cities have a well-developed network of subways or urban railways, which are able to provide mass transportation. The vast majority of large cities, especially those where the transport network and buildings have developed historically, are trying to ensure mass movement by developing a network of bus services and electric transport. Given the shortage of free space in the city, public transport mostly moves in the general traffic flow.

Spatial and time-based priorities are often used when implementing intelligent transport systems or their elements in public transport management. The essence of the implementation of the first is the arrangement of allocated lanes for public transport, and the second is the management of traffic lights according to the criterion of minimizing the delay of public transport rolling stock. The geometric parameters of the roadway are often an obstacle to the implementation of spatial priorities as, in addition to the prioritization of public transport, it is necessary to ensure the passage of the general traffic flow. Concerning time-based priorities, which are based on adaptive traffic light control regimes, certain obstacles arise at intersections where public transport moves from all approaches or at those signalized sections of the road network where there are short (50–100 m) distances between stop-lines. The experience of implementing the spatial priority for public transport on the streets of controlled motion shows that in such sections, traffic delays in the general traffic flow increase significantly. It is often due to the lack of coordinated operation on adjacent traffic lights. In addition, the need to meet the needs of pedestrians and other road users who use micro-mobility devices during their travel should also be taken into account. Such analysis confirms the need to form a justified integrated approach to solving problems with traffic delays, which would be different for each transport district or functional area of the city, based on the specifics of their operation. It is because each transport district is characterized by different specifics of the formation of transport and pedestrian passenger flows, built-up area density and configuration of the road network. Accordingly, there should be different approaches to road users' flows management.

2. RESEARCH STATEMENT

Implementation of coordinated traffic control provides the integration of all signalized intersections or pedestrian crossings into a single system of traffic lights with fixed-time control programs. The time parameters of such control are set based on traffic intensity, saturation flow, geometric parameters of the roadway, etc. In conditions of coordinated control, there may be one or more programs that are developed for some periods of the day. The most significant efficiency of each program is achieved at a constant value of the traffic intensity for which it is designed. At the same time, it is known that not all sections, even the arterial road network, have constant values of traffic intensity, which causes an excess or deficiency of the permissive signal in the timelines that connect all traffic light objects of the coordination system. In the urban transport system, the main public transport routes are mainly laid at such sections, which have peculiarities of motion different from the general traffic flow associated with downtime at bus stops. The significant share of public transport in the traffic flow on the arterial sections of streets with coordinated traffic often leads to the destruction of these time lanes. Based on this, it is necessary to ensure traffic coordination in such areas while giving public transport a spatial priority. It may cause some increase in traffic delays in the lanes allocated for the general traffic flow but reduce such delays for public transport rolling stock. In total, this will increase delays per vehicle with a simultaneous decrease per user (passenger). Such measures will be especially effective in those sections of the road network where significant passenger flows are observed.

3. RELEVANCE OF THE STUDY

Minimizing traffic delay at intersections is one of the main tasks of increasing road network functioning. The biggest problems with traffic delays occur at the intersections of arterial streets. It is known that the capacity of the whole street is determined by the intersection with the lowest value of this indicator. In conditions of constant significant traffic intensity, a queue of vehicles is gradually accumulating here, which is able to block adjacent intersections. Public transport is also idle in these traffic jams. Without proper prioritization measures, such a negative impact makes it an unattractive way to travel. It has a negative effect on attempts to encourage residents to choose this type of travel and destroys any effort to create an efficient transport system based on methodological approaches to developing sustainable urban mobility plans. Based on this, it is necessary to apply a hierarchical approach to minimize delays in traffic flows from the micro-level (solving the problem at isolated intersections) to the meso-level (effective management of intersection systems) and further to the macro-level (efficient and balanced mobility management in the city). Increasing the attractiveness of public transport by providing it with time-based and spatial priorities can significantly reduce the flow of individual transport, which minimizes the total time spent on travel and many environmental problems.

4. AIM AND THE TASKS OF THE STUDY

The aim of this study is the determination of the effectiveness of spatial priority for public transport in systems of coordinated traffic control at signalized sections of the arterial road network by delay minimization criteria.

For the achievement of the goal of the study, the following tasks are formulated:

- to determine time parameters of traffic light control and also traffic flow indicators that have the most significant and systemic impact on the formation of delays in it;
- to determine traffic intensity and traffic capacity at sections of the arterial street of controlled motion using the method of field research;
- to carry out the simulation modeling to determine the change of traffic delay at coordinated control in conditions of absence and presence of spatial priority for public transport;
- to justify the expediency of implementation of spatial priority for public transport in systems of coordinated control at multi-lane sections of arterial road network;

In this paper, field research methods to determine traffic flow indicators and simulation modeling to determine the change of traffic delay in this flow in different ways of their control are used.

5. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Implementation of traffic light control, regardless of the management method (fixed-time or flexible algorithms), requires considering the interests of both transport and pedestrians. For any algorithm, a minimum permissive signal duration should be set for pedestrians who execute their right to cross the roadway during this time and a maximum restrictive signal duration associated with their patient waiting. In papers [1–3], it is determined that for different city territories (transport districts), such time parameters are significantly different, based on the time of patient waiting for pedestrians. Consideration of the time of patient waiting allows reducing the number of violations of traffic light control regime by pedestrians. This impact factor must be considered in coordinated traffic control systems, where, in addition to signalized intersections, there are also stop-lines where only pedestrians or other road users who use micro-mobility devices are allowed to pass in the conflicting direction.

After considering the pedestrian and traffic flows, the construction of a timeline in coordinated traffic control systems begins, during which the uninterrupted passage of vehicles through the stop-lines of this system is provided. Particular attention should be paid to the groups of vehicles that pass through each of the stop-lines to ensure uninterrupted passage. These groups tend to dissipate during the movement due to two key factors – the homogeneity of the group and the length of the section [4]. Let us consider these two factors influencing the formation and dissipation of groups of vehicles in more detail.

The formation of a group of vehicles occurs on the restrictive signal and depends on the intensity of their arrival and the ratio between the permissive and restrictive signals in the traffic light control cycle [5]. During this process, the impact of the vehicle's dynamic size is minimal, so the degree of traffic flow heterogeneity is a relatively insignificant factor. The dissipation of a group of vehicles depends less on the intensity of their departure from the stop-line on the permissive signal and the time parameters of the traffic light cycle. Still, there is a more significant influence of the degree of heterogeneity of traffic flow. This effect increases as the distance between adjacent stop-lines increases, as cars have higher dynamic characteristics than trucks and buses (trolleybuses).

Regarding the length of the section between traffic light objects, this factor depends on the density of the road network and the location of signalized pedestrian crosswalks. The study [6] noted that the maximum length of the section between traffic light objects, which provides sufficient stability for the group, is 1200 m. At the same time, it is not noted what the traffic flow and the level of its transit (the share of direct vehicles at stop-lines) is by the degree of homogeneity (the share of cars). In addition, traffic intensity varies widely (200–600 cars/h per lane). In [7], similar patterns are achieved for a section length of 300 m and traffic intensity in the range of 400–600 cars/h per lane. The number of lanes per direction can explain this discrepancy in the coordinated control system, as this value is associated with the number of lane changes in the group of vehicles.

Based on the above, to ensure the passage of the whole group through the coordinated section without traffic delay can be by either limiting its speed parameters or providing a phase shift at adjacent stop-lines [7]. Having applied speed limits, one of the main advantages of coordination on arterial streets – providing the fast and uninterrupted passage of transit traffic flows is lost. Phase shift is also an ineffective solution as it increases delays in conflicting directions. In addition, if there is significant heterogeneity in traffic flow, it is necessary to shift the phases and increase the width of the timeline. Additional delays also occur for public transport rolling stock, the uninterrupted passage of which through the coordination system depends not only on its dynamic characteristics but also on the duration of the delay at stopping points. Such delays are determined by the intensity of public transport and indicators of the variability of passenger traffic at bus stops [8].

Particular attention should be paid to the study of the geometry of the road network when designing coordination systems, as the effectiveness of traffic management must be considered not only in a linear local context (one street or section) but also in spatial (transport district) [9]. This statement is relevant in conditions of the high density of the arterial road network. Simultaneous consideration of indicators of road users and the peculiarities of their behavior in places of interaction and planning characteristics of the roadway can be achieved using simulation, which is based on advanced models of Webster and Wiederman [10–12]. In this study, the emphasis is on using such models in fixed-time control algorithms. They are effective for traffic flow, characterized by the constant arrival of vehicles to the stop-line. This criterion best describes the regularities of traffic movement on the arterial streets.

Considering all these factors of the possible impact on the structuring of traffic flow during its passage through the system of signalized intersections (pedestrian crosswalks), we will focus on public transport. This analysis will be based on [13], which considers prioritization for public transport in the area of signalized local intersections, and on [14–16], where systemic prioritization at the level of traffic routes is considered. Local prioritization is mainly related to allocating a separate lane for public transport before intersections or the control of traffic lights at them using adaptive algorithms. The advantage of local prioritization is solving the problem of public transport delays at complicated intersections, but this principle of traffic management is challenging to integrate into the coordination system. At the same time, prioritization at the level of traffic routes is the best solution, as it allows combining related principles of organization and management of public transport in the system of adjacent intersections, including those unregulated by traffic lights. This analysis shows that the implementation of coordinated control can be considered on the sections of arterial streets with a significant intensity of public transport while ensuring simultaneous spatial prioritization for it. In addition, the study [17] noted the need for constant monitoring of the speed and intensity of traffic in such sections. Studies [18–20] indicated that such indicators require adjustment of fixed-time control programs adapted to their change in the whole coordination system to ensure the stability of groups of vehicles.

The effectiveness of coordinated control with ensuring the spatial prioritization of public transport will allow reducing the overall transport delays per user of the city's transport system, which travels using motorized transport [21].

6. PRESENTATION OF BASIC MATERIAL

Let`s consider the peculiarities of traffic flows on the section of an arterial street of controlled motion. All signalized intersections (pedestrian crosswalks) will be combined into one coordinated control system to ensure spatial prioritization of public transport by arranging allocated lanes in this section (Fig. 1).

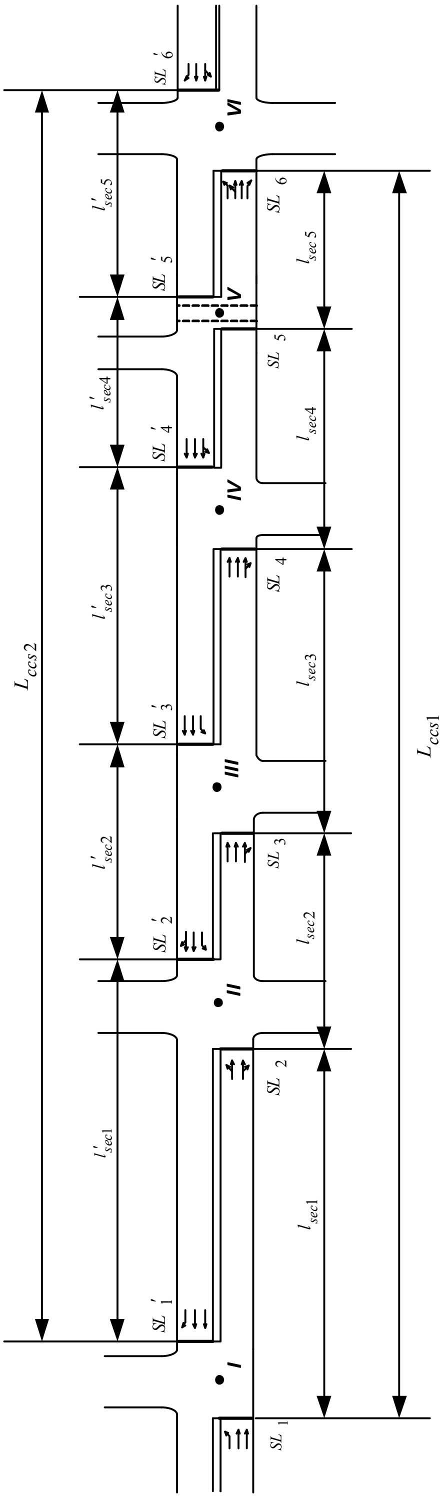

Fig. 1. Section of the arterial street of controlled motion

Based on the tasks of the study, as well as taking into account the planning features of this section (multi-lane and the presence of a dividing lane) and the proposed separate coordination of traffic flows and prioritization of public transport in both directions, it is divided into two parts – L_{ccs1} and L_{ccs2}. The first one, which indicated the direction I–VI (L_{ccs1}), has five sections between signalized objects (l_{sec1},…, l_{sec5}), where six stop-lines SL_1,...,SL_6 are located. The second one (L_{ccs2}), which indicates direction VI-I, has identical distribution by the number of sections between signalized objects and stop-lines. Lengths of investigated sections between signalized objects and the number of lanes at them are given in Table 1.

The prioritization of public transport in this section will be implemented due to its significant intensity. The following public transport routes operate here: 4 trolleybus routes with an intensity of 23 veh/h in one direction; 5 city bus routes with an intensity of 28 veh/h in one direction; 16 suburban routes with an average intensity of 2 veh/hour in one direction, as well as buses that provide transportation in intercity and international directions. As the street is an arterial of the city (Stryiska Str., Lviv), it is characterized by uneven traffic flow during peak periods in the directions of traffic. During the morning peak, traffic flows towards the center (I-VI) predominate, and during the evening peak period – from the center (VI-I). Along the entire length between the considered signalized intersections and pedestrian crosswalks, the street has three lanes in each direction, except for the section between intersections I and II, where there are two lanes.

Table 1

Planning characteristics of sections between intersections at the given section

Direction I-VI	Length of the section, m	Number of lanes	Direction VI-I	Length of the section, m	Number of lanes
l_{sec_1}	1000	2	l'_{sec_1}	1000	2
$l_{\text{sec}2}$	475	3	$l'_{\text{sec}2}$	475	3
$l_{\text{sec}3}$	700	3	$l'_{\text{sec}3}$	700	3
$l_{\text{sec}4}$	400	3	$l'_{\text{sec}4}$	400	3
$l_{\text{sec}5}$	450	3	$l'_{\text{sec}5}$	450	3

The results of other experimental measurements are following:

- taking into account that there is a fixed-time program of traffic control at traffic light objects at the section, by results of one-time measurement, time parameters of traffic light control are determined (Table 2).

Table 2

Time parameters of traffic light cycle at stop-lines

Number of stop-line	Duration of traffic light cycle components, s						Share of permissive signal in the cycle, %	
	initial (starting)			the next stop-line			initial	following
	t_p	t_r	T_c	t_p	t_r	T_c		
SL_1	53	37	90	43	47	95	53	43
SL_2	43	47	95	27	53	80	43	27
SL_3	27	53	80	36	34	70	27	36
SL_4	36	34	70	40	30	70	36	40
SL_5	40	30	70	30	95	125	40	30
SL_6	30	95	125	–	–	–	30	–
SL'_1	46	44	90	56	39	95	46	56
SL'_2	56	39	95	43	37	80	56	43
SL'_3	43	37	80	36	34	70	43	36
SL'_4	36	34	70	40	30	70	36	40
SL'_5	40	30	70	30	95	125	40	30
SL'_6	30	95	125	–	–	–	30	–

- measurement of traffic intensity (traffic accounting) was carried out during morning peak periods on weekdays (8:00–10:00) for direction I-VI and during evening peak periods (17:00–19:00) for direction VI-I. Accounting was carried out with the frequency of 1 cycle every 10 cycles to obtain representative averages over the hour. The results of these measurements are given in Table 3. In the future, they will also be used to determine the intensity of arrival of vehicles at adjacent stop lines.

Table 3

Traffic flow intensity on sections between stop-lines

Number of flow	Traffic intensity on lanes (p.c.u./h)			Share of cars on lanes, %		
	1	2	3	1	2	3
In direction L_{CCS_1} (I-VI)						
$l_{\sec_1}$	487	510	–	91	78	–
$l_{\sec 2}$	235	523	475	90	85	87
$l_{\sec 3}$	406	480	398	92	84	71
$l_{\sec 4}$	412	453	440	97	80	82
$l_{\sec 5}$	366	482	462	84	89	93
In direction L_{CCS2} (VI-I)						
$l'_{\sec_1}$	582	500	–	89	82	–
$l'_{\sec 2}$	407	534	432	96	90	85
$l'_{\sec 3}$	490	505	463	96	93	85
$l'_{\sec 4}$	502	495	378	98	95	80
$l'_{\sec 5}$	380	525	474	98	88	80

– determination of experimental values of the effectiveness of traffic light object operation was as follows. When the restrictive signal was activated, the number of vehicles approaching was recorded on each stop-line. Such registration lasts until the permissive signal is activated in each direction. The results of these measurements are recorded in column 4 of Table 4. They are necessary to determine the queue length depending on the intensity of arrival, duration of the delay for all vehicles at the stop-line and the duration of delay for one vehicle. Later, at the moment of activation of the permissive signal, the number and type of vehicles departing the stop-line were recorded, taking into account their further direction of movement. Results are recorded in column 6 of Table 4. They can be further considered when determining saturation flow, starting delay duration, and the relationship between the intensities of arrival and departure.

Table 4

Results of measurements of traffic delay at signalized intersections (pedestrian crosswalks) of the studied section

Measurement time: 8:00–10:00						
Movement direction – I–VI						
Stop-line	Traffic light cycle duration, T_C , s	Restrictive signal duration, t_r , s	The average number of stopped vehicles for 5 cycles, $\overline{n_{st}}$, units	Permissive signal duration, t_p , s	The average number of vehicles that passed the stop-line for 5 cycles, $\overline{n_{pas}}$, units	Number of cycles in which 1 vehicle waited, n_c
1	2	3	4	5	6	7
SL_1	90	37	16.6	53	18	0.92
SL_2	95	47	22.6	48	24.6	0.92
SL_3	80	53	35.6	27	30.2	1.18

Table continuation 4

1	2	3	4	5	6	7
SL_4	70	34	33.4	36	33.2	1
SL_5	70	30	39.6	40	39.6	1
SL_6	125	95	84	30	33.6	2.5
Measurement time: 17:00–19:00						
Movement direction – VI–I						
SL'_1	90	44	31.4	46	40.2	0.78
SL'_2	95	39	38.2	56	49.4	0.77
SL'_3	80	37	47.2	43	41.8	1.13
SL'_4	70	34	38.6	36	38.6	1
SL'_5	70	30	31.2	40	39.6	0.79
SL'_6	125	95	81.4	30	34.6	2.35

When assessing traffic conditions at signalized sections of urban streets with fixed-time control programs, it is necessary to pay special attention to the duration of restrictive and permissive signals and their share in the duration of the traffic light cycle. It allows determining the time while traffic flow accumulates and time while it dissipates. Thus, we can say that the traffic conditions in the studied section of the street correspond to three typical situations, based on the number of vehicles that pass the stop-line for one traffic light cycle. The first: if $n_c<1.0$ – then all vehicles that arrived at the restrictive signal passed the stop-line at the permissive signal and a particular time in the phase remained when there was no motion (the cycle structure is imbalanced, the phase distribution is ineffective). The second: if $n_c<1.0$ – then all vehicles that arrived at the restrictive signal of traffic light passed the stop-line at permissive signal without remaining time in the phase (the structure of the cycle is totally balanced; phase distribution is effective). The third: if $n_c>1.0$ – then not all vehicles that arrived at restrictive signal of traffic light passed the stop-line at permissive signal and queue accumulation begun (the structure of the cycle can be imbalanced and phase distribution ineffective, but detailed analysis of road conditions at conflicting directions is needed).

Analyzing the results of measurements, which are given in Table 4, we pay special attention to the number of cycles required by one vehicle to pass the stop-line. In the direction I–VI for the passage of stop-lines SL_1,..., SL_6, indicator n_c is respectively: 0.92; 0.92; 1.18; 1.0; 1.0; 2.5. The largest delays appear at stop-lines of intersections III and VI. The vehicle needs time equivalent to 1.18 of the existing traffic light cycle duration of 125 s to pass the first one. There was no additional delay on all other stop-lines, except for the one caused by the duration of the restrictive signal.

On the direction VI-I, to pass the stop-lines SL'_6,..., SL'_1, one vehicle needs respectively 0.78; 0.77; 1.13; 1.0; 0.79; 2.35 from the existing traffic light cycles duration. Here, we can observe analogies with direction I–VI, where values n_c are 1.13 and 2.35 for stop-lines at intersections III and VI, respectively.

The duration of delay is determined on lanes that serve the direct traffic flows in both directions taking into account the results of measurements given in Table 3 and Table 4. Some of these lanes also serve the turning flows, the impact of which is considered during the measurement of intensity.

Summary values of the intensity of direct flows on the lanes and traffic delays, expressed by the travel time of all approaches (stop-lines), are shown in Table 5.

The average time losses by one vehicle on the passage of every stop-line is determined by analysing the research results from Table 5. For intersections III and VI, where $n_c>1.0$, further we will carry out the modeling to determine the optimal time parameters of traffic light control for two different traffic control schemes – a system of coordinated control without prioritization of public transport and a system of coordinated control with its prioritization.

Table 5

Results of experimental measurements of traffic delay in direct traffic flow at stop-lines

PNumber of stop-line	The intensity of arrival to stop-line, auto/h	The intensity of departure (dissipation of queue at permissive signal), auto/h	Duration of restrictive signal, t_r , s	Traffic light cycle duration, T_c , c	Number of cycles, which one vehicle waited, n_c	Average time losses of one vehicle on the passage of intersection[1], s
SL_1	664	720	37	90	0.92	18.5
SL_2	857	932	47	95	0.92	23.5
SL_3	1602	1359	53	80	1.18	94.4
SL_4	1718	1707	34	70	1.0	17.0
SL_5	2037	2037	30	70	1.0	15.0
SL_6	2419	968	95	125	2.5	312.5
SL_1'	1680	1608	44	90	0.78	22.0
SL_2'	1448	1872	39	95	0.77	19.5
SL_3'	2124	1908	37	80	1.13	90.0
SL_4'	1985	1985	34	70	1.0	17.0
SL_5'	1605	2037	30	70	0.79	15.0
SL_6'	2344	996	95	125	2.35	295.2

Note. [1] *Average time losses are determined as product* $T_c \cdot n_c$. *For stop-lines where* $n_c \le 1.0$, *the average duration of passage of one vehicle is taken equal to half of the restrictive signal.*

During the research of processes of queue accumulation, it is necessary to consider the condition that one vehicle, which had not passed the stop-line at the permissive signal, will not necessarily pass this stop-line at the next one. It means that a specific period may be two or more cycles when the vehicle crosses the stop-line.

From the analysis of Table 4 and Table 5 (a number of cycles spent by one vehicle on the stop line), we can say that the least delays (less than one traffic light cycle) are at stop-lines where in the appropriate phase is significant (over 45 %) share of permissive signal in the direction.

In practice, it is not always possible to implement a sufficient duration of the permissive signal as such a decision may lead to the formation of large (in length and duration) queues of vehicles in conflicting directions. However, if the direction is the arterial one, and with the introduction of coordinated traffic light control or prioritization for public transport, increasing the permissive signal in this direction is not only a reasonable solution but also considered justified. It is because the reduction of traffic delay is achieved with the binding per one vehicle and per user of the transport network. Let`s make the corresponding substantiation within the limits of this research concerning the expediency of implementation of long cycles with a considerable share of a permissive signal in them.

Based on the measurement results shown in Table 5, the arrival intensity is grouped into three ranges: less than 0.25 auto/s (equivalent 900 auto/h); from 0.25 to 0.50 auto/s (equivalent 900–1800 auto/h); from 0.50 to 0.75 s (equivalent 1800–2700 auto/h). Applying such grouping by arrival intensity, we mean the whole approach, not a separate lane. Then in PTV VISSIM we will determine the maximum possible length of the queue of vehicles which may occur in the lane for direct traffic flows before the signalized intersection (pedestrian crosswalk) depending on the intensity of arrival of vehicles and the share of the permissive signal in the traffic light cycle with a maximum duration of 125 s (Fig. 2).

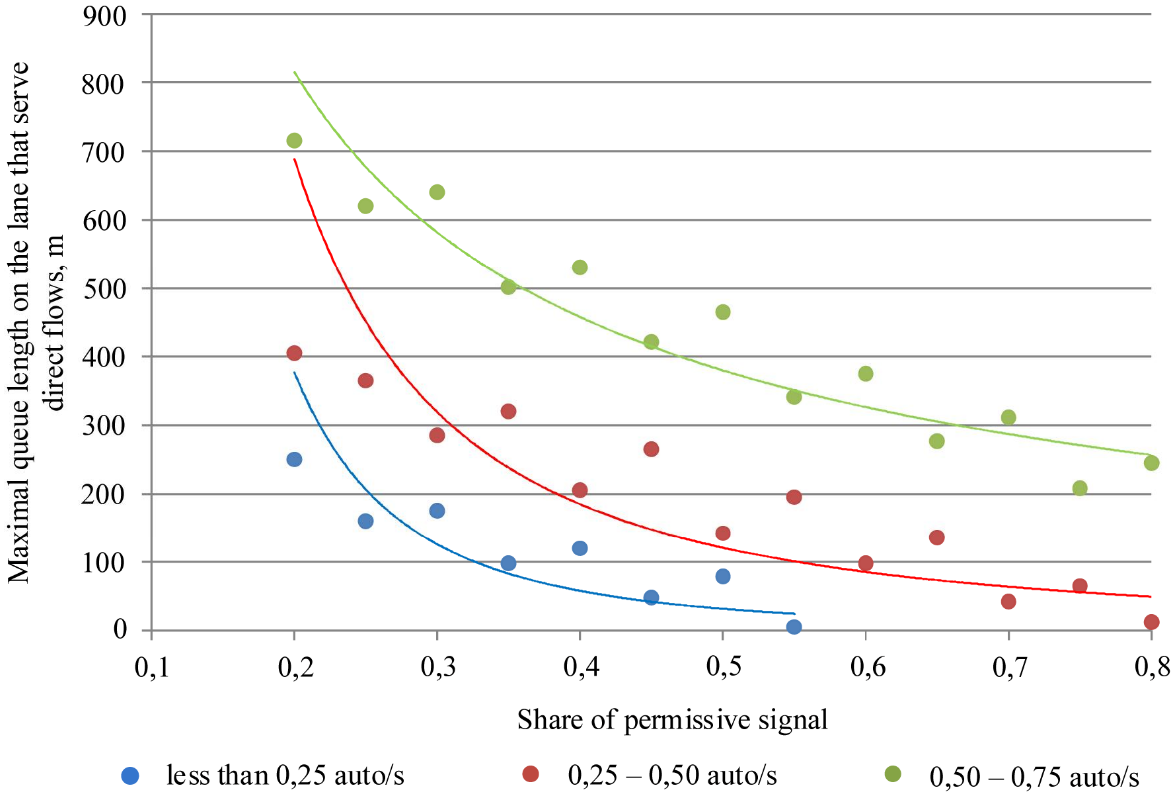

Fig. 2. Results of simulation of the change of maximal queue length depending on the time parameters of traffic light cycle

After analyzing these simulation results, it is possible to predict possible queues formed in traffic flows depending on the number of lanes and the length of the section between stop-lines, the intensity of arrival of vehicles at the intersection and the time parameters of traffic light control. Simultaneous comparison of experimental measurements and simulation results makes it possible to compare the differences between experimental and theoretical data. Also, it provides an opportunity to determine the maximal queue length that can appear before the stop-line and the “accumulative” ability of the section between stop-lines (meaning the distance between two adjacent stop-lines). It is an essential aspect of setting the time parameters of traffic light control at different densities of the road network.

When the intensity of arrival is less than 0.25 auto/s, the maximal queue length which can appear before the stop-line of signalized intersection (pedestrian crosswalk) is about 400 m, given that the share of permissive signal in the traffic light cycle is 0.20–0.55.

Given that there were no cycles with a share of the permissive signal of more than 0.80 on the studied section and that the simulation model indicated the existence of large queues in secondary directions, the limitations were set for this study. The intensity of arrival of vehicles to the intersection should not exceed 0.75 auto/s in the three-lane direction; the share of the permissive signal in the traffic light control cycles is 0.20–0.80 (this range of values allows to cover almost all possible modes of traffic light control).

The next stage of modeling is to determine the delay in traffic movement depending on the change of the control mode in three states:

State 1: the current state of the traffic flow, traffic light control regime and traffic conditions (base model);

State 2: implementation of coordinated control with such limitations at all traffic light objects of experimental section: duration of the permissive signal is no less than 56 s (based on parameters of control at “leading intersection” II in direction VI–I) provided that its share in traffic light cycle will be no less than 0.45. However, the priority for public transport is not set;

State 3: coordinated control with simultaneous provision of spatial priority (allocated lane) during the passage of public transport in the right lane is implemented. Time parameters of traffic light control are identical to the system without priority (State 2).

Having taken into account all the main parameters necessary to form the transport model in PTV VISSIM, and after its calibration and verification, we obtained the data at every simulated state (Table 6).

Table 6

Comparative analysis of the change of delay by results of an implementation of measures for improving the traffic control on the section of the arterial street of controlled motion

Number of stop-line	Simulation results – duration of delay of one vehicle at stop-line						
	State 1 (base model), s	State 2 (coordination without priority), s	Change (comparing with base), %	State 3 (coordination with priority), s		Change (comparing with base), %	
				GF[1]	PT[2]	GF[1]	PT[2]
SL_1	18.5	9.1	-49	20.7	8.3	+12	-45
SL_2	23.5	11.3	-48	27.3	8.5	+16	-36
SL_3	94.4	49.6	-53	103.0	28.1	+10	-30
SL_4	17.0	6.0	-35	19.0	8.3	+12	-49
SL_5	15.0	5.1	-34	17.9	7.5	+19	-50
SL_6	312.5	144.1	-46	372.7	78.3	+19	-25
SL'_1	22	5.5	-25	25.1	9.2	+14	-42
SL'_2	19.5	5.5	-28	21.5	9.0	+10	-46
SL'_3	90	52.2	-58	106.2	24.3	+18	-27
SL'_4	17	3.6	-21	19.0	7.7	+12	-45
SL'_5	15	3.6	-24	17.9	6.2	+19	-41
SL'_6	295.2	150.6	-51	346.9	79.7	+18	-27

Note. [1]GF – general traffic flow; [2]PT – public transport.

The advantage of the *State 2* model is that it provides long (by time) transit traffic through all intersections, and the advantage of the *State 3* model is the higher capacity per user of the transport network (including those traveling by public transport). The most precise calculations of the effectiveness of such design solutions can be established when experimental measurements of passenger flow capacity are also performed. Graphical results of the simulation are shown in Fig. 3 and Fig. 4, where, respectively, the value of the delay of traffic flow in the directions I-VI and VI-I are given.

According to the results of the analysis of Fig. 3 and Fig. 4, we can say that the most “problematic” in terms of efficiency of transport services, based on the criterion of the least time spent on transportation of transport network users, are and will remain stop-lines (signalized intersections, pedestrian crosswalks) III and VI. In the direction I–VI, the model State 2 on these critical stop-lines managed to reduce the delay of traffic and vehicles by 44 s (53 %) and 169.1 s (46 %) compared to the model State 1 (current state). In this direction, in the model State 3 at stop-lines III and VI, delays for one vehicle of general traffic flow increase by 9.4 s (10 %) and 59.5 s (19 %) compared to the model State 1.

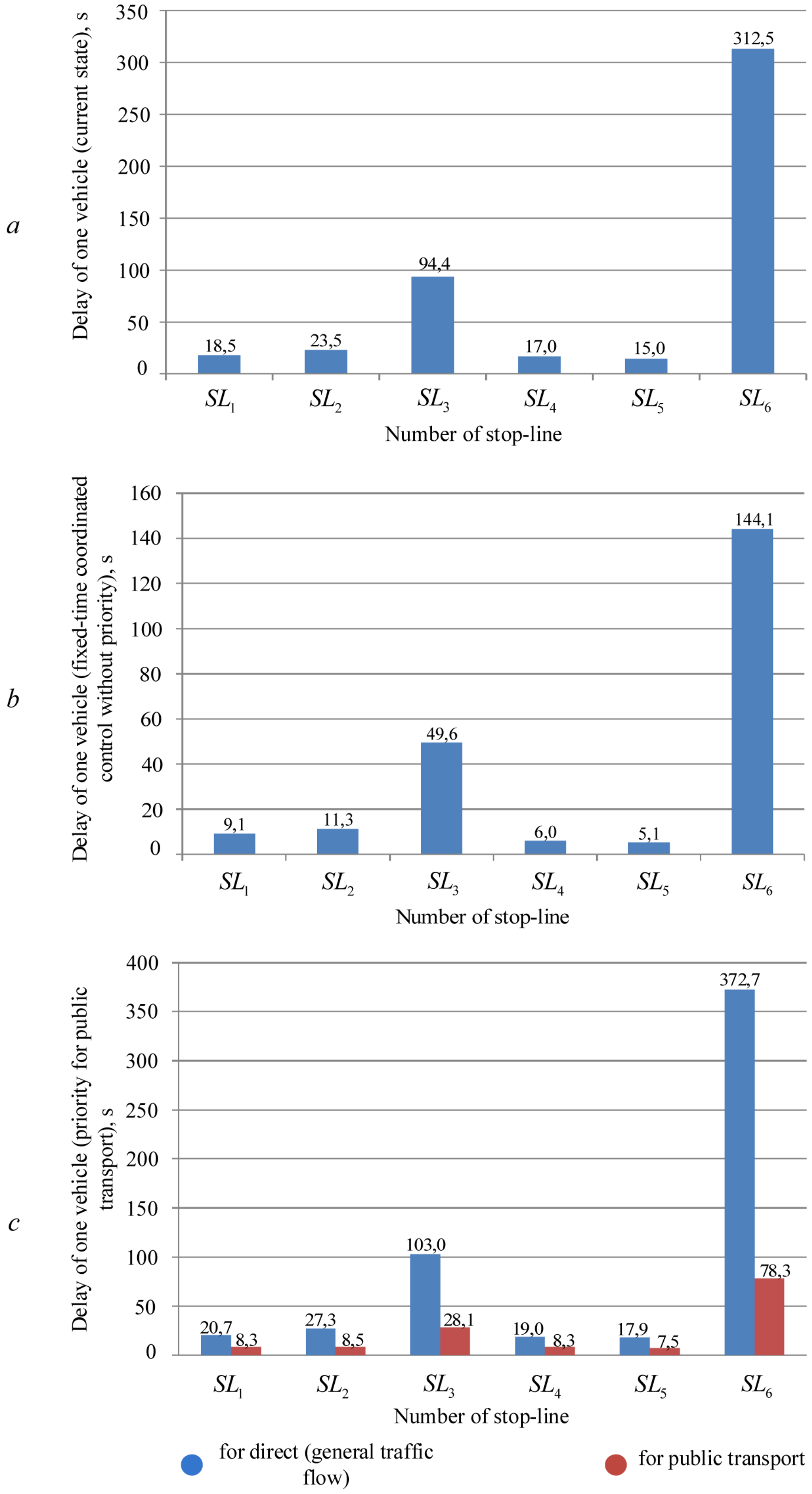

Fig. 3. Results of simulation to determine the duration of the delay at different states of traffic flow on the street section (direction I–VI):
a – State 1;
b – State 2;
c – State 3.

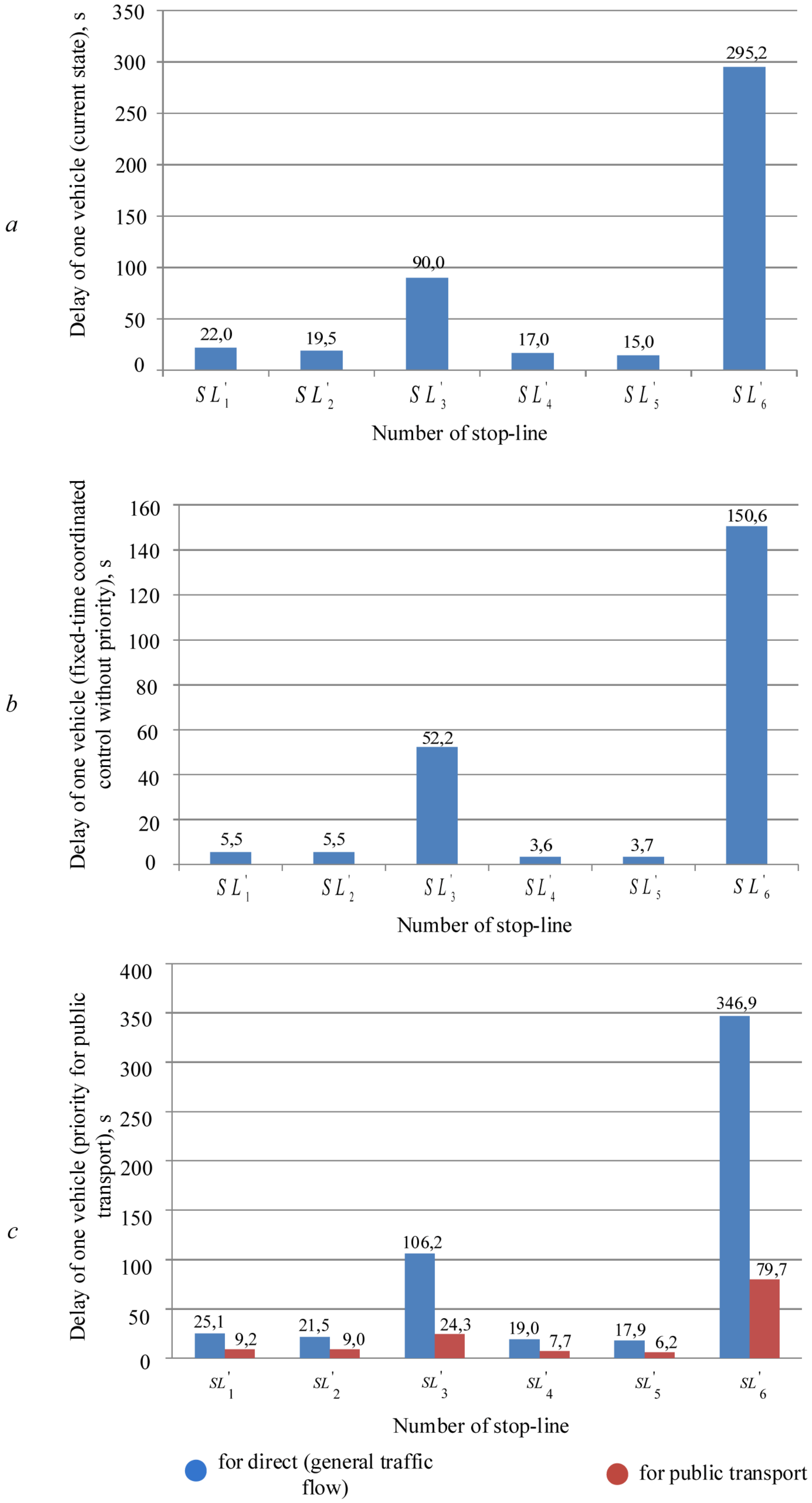

Fig. 4. Results of simulation to determine the duration of delay at different states of traffic flow on the street section (direction VI–I):
a – State 1;
b – State 2;
c – State 3.

In addition, a significant effect is achieved for public transport in the State 3 model compared to the base model (State 1) and the State 2 model. Thus, in the direction I-VI, its delay at stop-line III is reduced by approximately 3.3 times for the State 1 model and 1.8 times for the State 2 model, and for stop-line VI, this reduction is about four times for State 1 model and 1.8 times for State 2 model. A similar situation is observed in the direction VI-I. On stop-line III, the reduction is approximately 3.7 times for State 1 model and 2.1 times for State 2 model, and for stop-line VI, this reduction is about 3.7 times for State 1 model and 1.9 times for State 2 model.

In summary, it can be stated that a significant reduction in time spent on signalized intersections (pedestrian crosswalks) by public transport in coordinated traffic control systems while giving it a spatial priority and justification for the implementation of long permissive signals with their significant share in the control cycle in arterial directions.

7. CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVES

By results of this research, such conclusions can be made:

a) the most important factors that affect the efficiency of coordinated traffic control systems are: the width of the roadway and the number and specialization of lanes; intensity, composition and direction of traffic flow; the distance between adjacent stop-lines; the share of the permissive signal in the traffic light control cycle;

b) the main task when designing coordinated traffic control systems is to ensure the stable dynamic performance of a group of vehicles and optimal shift of phases of traffic light control with timelines that are able to pass this group through all stop-lines of the system;

c) to minimize traffic delays in coordinated control systems on the arterial sections of urban streets of controlled motion with three lanes in one direction, it is necessary to achieve a share of the permissive signal of more than 45 % in control cycles with a duration of 80–125 s at traffic intensity limits of 500–600 auto/h per one lane. With such time parameters and the absence of spatial priority for public transport, it is possible to achieve an average reduction in traffic delay of about 40 % for all intersections of the coordination system compared to traffic delays at signalized intersections with fixed-time local control. The implementation of a spatial priority for public transport in the form of allocated lanes in the coordination system increases the delay of the general traffic flow by 15 % and reduces it by about 40 % for public transport compared to local control.

d) in coordinated control systems in three-lane directions, where there is no spatial priority for public transport and the maximum duration of the traffic light cycle of 125 s, the maximum queue length can reach the following values: about 400 m at an intensity of arrival of 0.25 auto/s; about 700 m with an intensity of arrival of 0.25–0.50 auto/s; about 850 m with an intensity of arrival of 0.50–0.75 auto/s.

Further research on the problems of public transport delays in coordinated control systems is as follows:

- determination of the impact of right-turn traffic intensity on public transport delay, which is provided with spatial priority;
- investigation of the amount of passenger flow that allows determining traffic delay per one user of transport system – driver and passenger more precisely.

Such research will allow the implementation of such systems of coordinated traffic control on arterial streets, which are based on the provision of spatial and time-based priority for public transport.

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МІНІМІЗАЦІЯ ЗАТРИМОК ГРОМАДСЬКОГО ТРАНСПОРТУ НА МАГІСТРАЛЬНИХ ВУЛИЦЯХ З КООРДИНОВАНИМ РУХОМ

Анотація. *У роботі наведено результати досліджень, за допомогою яких удосконалено метод мінімізації затримки громадського транспорту на перехрестях, де діє система координованого управління рухом. Такі транспортні дослідження проводились із одночасним застосуванням натурних вимірювань із вивчення показників транспортного потоку та імітаційного моделювання у PTV VISSIM для перевірки рівня ефективності роботи координованого управління та достовірності отриманих результатів. Суть методу полягає в тому, що досягається зменшення затримки в русі із розрахунку на одного користувача транспортної системи під час його переміщення регульованою ділянкою вулично-дорожньої мережі. Ефективність цього методу досягається за умови значної інтенсивності громадського транспорту, якому забезпечується просторовий пріоритет у вигляді виділеної смуги. Обов'язковими показниками та параметрами є незмінність кількості смуг руху на ділянці, де відбувається координація, а також високий рівень транзитності (понад 70 %) прямих транспортних потоків. Результат досягається за існування таких фаз на напрямку координованого управління, частка дозвільного сигналу у яких становить понад 45 % від тривалості циклу з обмеженнями тривалості 90–125 с. За таких параметрів мінімізуються стартові затримки загального транспортного потоку на стоп-лініях і досягаються максимальні значення потоку насичення. До того ж, встановлюється достатня ширина стрічки часу для проїзду громадським транспортом регульованих ділянок. Певна затримка громадського транспорту у такій системі управління все ж виникає, проте вона пов'язана із його затримками на зупинкових пунктах. Упровадження таких систем координованого управління рухом рекомендується на магістральних вулицях загальноміського значення регульованого руху з відстанню між суміжними стоп-лініями не більше 800 м. Таке обмеження дозволяє уникнути розпаду груп транспортних засобів.*

Ключові слова: *координоване управління рухом, жорстке програмне управління, магістральна вулиця, транспортні дослідження, транспортний потік, громадський транспорт, тривалість світлофорного циклу, імітаційне моделювання, інтенсивність руху, склад транспортного потоку.*