CHOOSING THE OPTIMAL METHOD TO PROVIDE PUBLIC TRANSPORTATION PRIORITY

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ABSTRACT
The article proves that the traffic intensity of cars and buses is uneven both during the day and within 1 h. The dependences of the vehicles delay time when passing the intersection with five ways of providing the priority of public transport (PT) are given. The considered methods are divided into three groups: dedicated lane (passive), traffic light adaptive control (active priority) and combined options (combination of active and passive). To select the optimal method of priority in work, the users total delay time is used, taking into account the drivers and passengers time loss in private and public transport. An estimate of the total delay time was determined using the traffic simulation in PTV Vissim. Algorithms for adaptive control of a traffic light object were developed in the VisVap module.

The best way to grant priority is different for different traffic levels at an intersection. At low traffic intensities of cars and buses, the combined method (dedicated lane and "green extension") is optimal. At high traffic intensities and a small number of passengers, the "green extension" becomes the best way.

As the number of passengers on the bus increases, the effect of each method of granting PT priority changes to a different extent. So, at high traffic intensities, the combined method becomes optimal (dedicated lane and "green extension").

Differentiation of the methods of providing the priority of PT in space and in time allows you to get the least loss of time for movement for each local section of the street and time period.
Keywords: active priority, intelligent transportation systems, public transport priority, public transport, transport modelling.

1 INTRODUCTION

In recent years, the concept of "Mobility-as-a-Service (MaaS)" has been actively implemented in cities around the world. The level of development and quality of work of public transport (PT) plays an important role in promoting the concept of MaaS [1]. Countries with a low level of public transport development have a lower rate of implementation of MaaS than countries with a high quality of public transport operation. The efficiency of public transport operation depends on the connectivity of the territories, the density of the road traffic network, and the route network [2]. However, if these parameters cannot be improved, then the municipal authorities need to improve other parameters, for example, increase the communication speed.

People who mainly use public transport and who do not have a car and the opportunity to use "active transport" for travel are less susceptible to a decrease in the quality of transport services [3]. The authors of the study note that before changing the transport system to increase sustainable mobility, the goals of these changes must first be clearly outlined. This is important for choosing the most effective measures for the development of the city's transport complex.

The development of intelligent transportation systems (ITS) plays an important role in improving the road situation. The ITS operation settings take into account not only the level of traffic loading and traffic delays at traffic lights but also the ambient air pollution by the exhaust gases of cars [4].

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In the future, the use of unmanned vehicles will increase traffic density and capacity by reducing the distance between cars. This must be taken into consideration in the future during simulation modelling to correct the model of following the leader and when setting up algorithms for adaptive control of traffic lights in ITS [5]. At the moment, reducing time delays at intersections remains relevant, including through ensuring public transport priority when crossing intersections.

In [6], when setting up an algorithm for controlling bus priority at an intersection, the authors consider not only the delay time but also the quantity of harmful substances emitted by categories of vehicles. Controlling priority at intersections reduces the delay time of public transport, ensures the movement of buses on schedule, and improves the awareness of passengers at stops about the time of arrival of the bus [7]. The priority of bus passing at intersections is also used to restrain PT rolling stock in order to prevent their congestion at the downstream bus stop [8].

In addition to the positive effect for public transport from the use of priority when crossing intersections, traffic parameters for other categories of vehicles degrade, including for vehicles moving in directions intersecting with PT [9, 10]. In [11], two scenarios of the priority of crossing intersections by trams are considered: unconditional priority and conditional priority versus “do nothing”. For the section under consideration, unconditional priority leads to significant deterioration and loss of time for all road users. The use of conditional priority has reduced the loss of time.

The authors in [12] consider the priority of PT travel along a bus lane with an additional traffic signal (pre-signal) [12]. The study took into account flow rates, bus frequencies, and bus passenger occupancies. The priority of crossing intersections in combination with additional road signs and markings makes it possible to implement priority for buses that move not only in separate directions but also in a separate lane [13]. The work gives an example of applying tandem design for buses making a left turn at an intersection.

A dedicated PT lane significantly increases the speed of communication, especially during peak hours. It allows the bus to drive up to the intersection, that is, to reduce the loss of time even without changing the traffic light control parameters. During inter-peak times, when there are no difficulties in the movement of buses between intersections, it is possible to reduce the loss of travel time from PT using active priority methods [14, 15].

There are three most common ways to provide active PT priority [16]:

(1) Green extension. It is used in cases where the bus does not have time to pass the stop line at the permissive traffic light, then the duration of the phase is extended by the time required to pass through the intersection of this bus. This method gives a great effect for a small number of buses, since in this case the bus does not stop at the red traffic signal in front of the intersection.
(2) Stage recall. It is used in cases where, in front of the intersection at the time of the traffic light red signal, a sufficient number of buses accumulate to operate, and then the green signal turns on earlier. In this case, there is a small effect for a large number of buses.
(3) Stage skipping. With this method, to ensure the movement of buses, the order of the traffic light control cycle phases is changed.
(4) Simulation modelling is used to assess the effectiveness of the algorithms for creating PT priorities [16, 17]. In [18], the results of modelling in the Vissim program show that when bus priority at intersections was applied, there was an effect and a decrease in delay time of about 21%. The aim of the study is to develop a methodology for the

rational use of active priority methods for buses when passing regulated intersections. The methodology is based on the patterns of formation and change of the delay time in the movement of public transport, taking into account the number of passengers in public transport and the loss of time for all participants in the movement.

2 MATERIALS AND METHODS

The total time of the bus movement on the section of the road network, including the stopping point and the stage to the intersection, consists of three components:

$$T^{\mathrm{PT}} = t_{mov} + t_{\mathrm{stopline}} + t_{\mathrm{busstop}}, \tag{1}$$

where t_{mov} – time in motion, t_{stopline} – standing time in front of the intersection, t_{busstop} – time at the bus stop.

A preliminary experiment showed that on a section of the main street of regulated traffic, 134 m long, 68% of the buses approached the stop line at a red traffic light. For these buses, standing time losses have formed (Fig. 1). The loss of standing time at a regulated intersection is 43%, 20% of the time falls on the movement of buses and 37% on boarding/disembarking passengers at a stopping point. The paper discusses methods to reduce the loss of time for buses and passengers when passing through a regulated intersection.

The approach of buses to the stop line is uneven. The largest part of the buses approached in the middle of the cycle (from 36 to 71 s). This part came up in the second half of the phase with the red light, when 50% of the red was realized, and 32% remained before the green light was turned on.

In the last quarter of the cycle green time, 29% of the buses pass the stop line. This is possible due to the movement along a dedicated lane and an increase in the speed of buses (Fig. 2). The less time remains before the green signal is turned on, the higher the speed of the bus in order to have time to pass the intersection to the green light.

Despite the presence of a dedicated lane for PT and an increase in speed by 1.5–2 times, some (17%) of the buses approached the stop line within 10 s after the green signal was

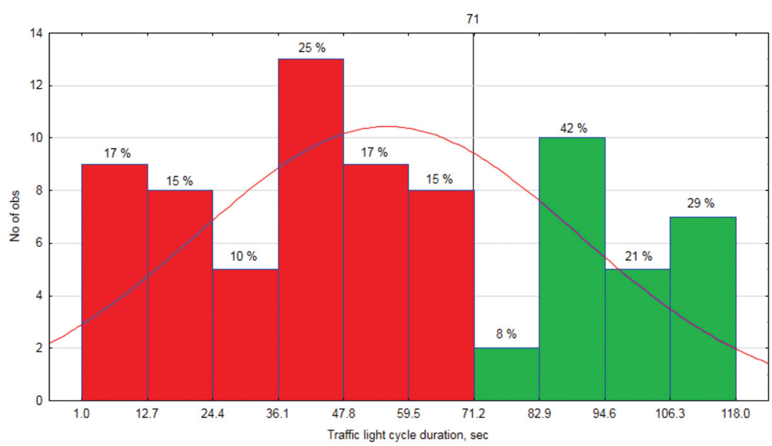

Figure 1: Distribution of bus arrival times relative to the duration of the traffic light control cycle.

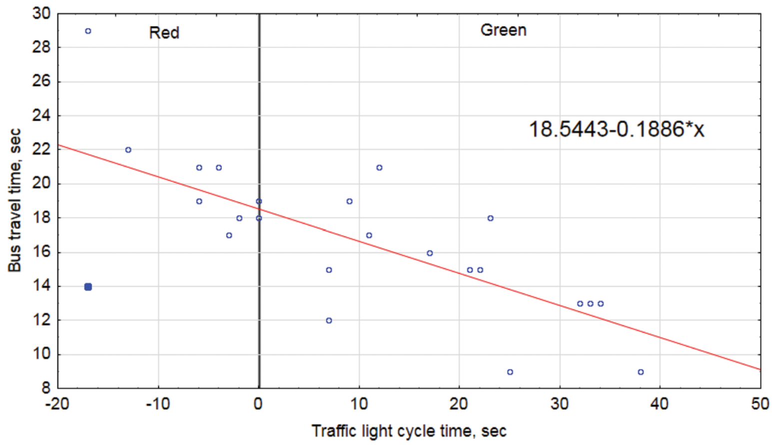

Figure 2: Dependence of the movement time in the section before the intersection to the stop line from the moment of the bus approach relative to the traffic light cycle duration.

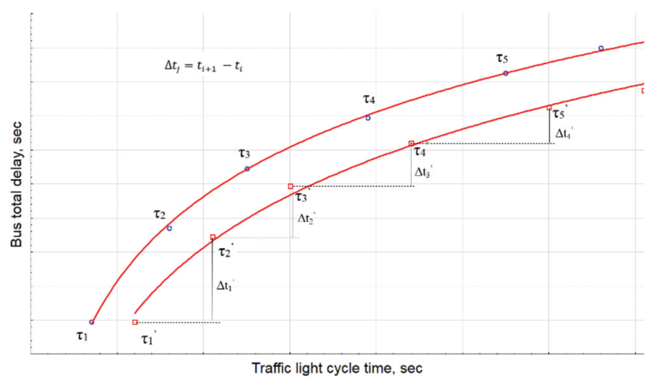

Figure 3: Theoretical view of the dependence of the total delay on the number of buses and stopping times (t_i – the loss of time for each ith bus standing in front of the intersection).

turned on. This indicates the possibility of reducing the loss of time for buses at the intersection by adjusting the mode of operation of the traffic light.

The formation of PT time losses at the stop line depends on the moment of arrival of the bus relative to the total duration of the cycle. The earlier the buses arrive relative to the beginning of the green signal and the more there are, the higher the total delay time of the buses for the traffic light control cycle will be. The total delay time is the sum of time losses during the jth cycle of the nth number of buses that arrived, respectively, at time points $t1$, $t2$, …, tn (Fig. 3).

The increase in the total delay time for each approached bus is formed from the time that the bus will stand waiting for the permissive traffic light signal, minus the similar delay time of the previous approached bus. In this case, the logarithmic model describes the total time losses (2) under a number of conditions:

1. The increase in total time losses from each bus that stopped on the way to the intersection is less than the increase in time losses from the previous one ($\Delta t_j > \Delta t_{j+1}$).
2. The number of points is determined by the number of buses and $j \in [1, n\text{-}1]$, $i \in [1,n]$.

$$t^{\text{pt}}_{\text{delay}\,j} = a \cdot \ln\left(b \cdot \tau_i\right), \tag{2}$$

where τ_i is the moment when the *i*th bus stops in front of the intersection relative to the duration of the green signal (the moment of stopping), Δt_j is the increase in the total delay time between *i* and *i*+1 buses.

When calculating this indicator, the first bus that arrives and stops has the highest weight, since it sets a high initial value for the delay. If priority is given to the movement of this bus, it is possible to significantly reduce the accumulated standing delay time during the period of the green signal.

In the case of a later arrival of buses ($\tau_i' > \tau_i$), a decrease in the total delay time is observed, since each arriving bus has less time loss ($t_i' < t_i$).

A possible type of pattern of influence of the distribution of the approach of buses for the duration of the red traffic signal (t_{red}) on the total delay time: total delay time (Y_{max}, 0); approach moment (0, t_{red}).

This type of dependence is formed as a series of special cases at the moment of approach and does not allow estimating the loss of time at any time between events. To take into account the time loss of the bus at any time of the red traffic signal, it is necessary to express the formation of time losses as a continuous process. The total delay time is the loss of time of the *n*th number of buses at time t, waiting for the enabling signal of the traffic light to turn on (Fig. 4).

$$t^{\text{pt}}_{\text{delay}\,j} = a \cdot e^{b \cdot \tau}, \tag{3}$$

When considering the continuous process of bus delay time formation (t_i) during the period of the green signal, the intensity of the increase in the total time losses (Δt_j) increases with each approaching bus and at earlier moments of their stop in front of the intersection relative to the duration of the green signal (τ_i). The number of buses at a particular time of the duration of the red traffic signal determines the intensity of the increase in the total delay time.

$$t^{\text{pt}}_{\text{delay}\,j} = \mathrm{f}\left(\tau_i, n_{\text{aBT}}\right) \tag{4}$$

With a smaller number of buses that arrived evenly during the duration of the red traffic signal, the total delay time will be less. However, if a smaller number of buses approach at the beginning of the red traffic signal, then the total delay time may be longer.

Within the framework of the concept of priority to the movement of public transport, the municipal authorities and organizers of transportation are faced with the task of minimizing the delay time of public transport.

$$T^{\text{pt}}_{\text{delay}} = \sum\nolimits_{j=1}^{n_{\text{cycles}}} t^{\text{pt}}_{\text{delay}\,j} \rightarrow min. \tag{5}$$

To implement this task, there are methods of active and passive PT priority, which have different degrees of effect. However, it is not possible to conduct an experiment to assess the impact of PT priority methods on the parameters of the movement of personal and public transport in real conditions.

To assess the change in traffic parameters when the public transport priority (PTP) was implemented, traffic simulation was used in the PTV Vissim 11 program. A model of an regulated X-shaped intersection of two highways with six traffic lanes was created. Despite the equal intensity, the direction with the movement of buses in this work is considered the main one, the other direction is secondary. The traffic flow at the intersection are the same in all directions. Thus, the model used the same phase coefficients when the traffic light was operating. When creating a simulation model, the standard settings of the PTV Vissim program were modified according the real traffic parameters. Three phases of traffic light regulation were used in the model: movement of main direction, movement of secondary directions, and a separated pedestrian phase.

The transport model considers land-based urban public transport, the routes of which are laid along public roads (bus, trolleybus). Car traffic is variable and ranges from 1,600 to 2,060 vehicles/h at each approach to an intersection. Bus traffic ranges from 20 to 120 vehicles/h at each approach to an intersection.

During the simulation, six micromodels were created:

1. Basic option (no PTP).
2. Creation of a bus lane by reducing lanes for personal transport from three to two (passive PTP). In the Russian Federation, it is customary to convert the right lane into a bus lane and allow cars to turn right through this lane.
3. "Green extension" (active PTP). When a bus approaches an intersection and does not have time to cross the stop line at a permitting traffic light, the phase is extended.
4. "Stage recall" (active PTP). If there are six buses in queue in total in the priority direction, the phase is turned on early.
5. Combination of bus lane and "green extension".
6. Combination of bus lane and "stage recall".
7. In all simulation scenarios, the cycle time is constant. The maximum change in the duration of the permitting signal time when using adaptive control is 25% of its maximum duration.

For each of the options, measurements were made at different traffic flow rates. The following key indicators were used:

1. Average speed of vehicles in certain directions and in the node.
2. Average delay time of vehicles in certain directions and in the node.

3 RESULTS

To test the hypotheses, a section of the road network with an adjustable intersection in Tyumen was selected and observations were made for 5 working days for 30 min in the evening during the period of maximum traffic intensity. Observations were carried out at the same time under the same weather and road conditions. The site is characterized by the presence of a dedicated lane for the movement of buses on the way to the X-shaped intersection. During the observation, the moments of buses entry to the site, the moment of crossing or stopping in front of the intersection were recorded. The duration of the traffic light control cycle was 121 s, of which 50 s for the studied direction was the green signal of the traffic light. The duration of the red traffic signal was 71 s. With an hourly bus traffic volume of 142 vehicles and 30 traffic light control cycles per hour, from 0 to 7 buses approached the intersection for each cycle (Fig. 4).

In the cycle of traffic light control with a bus delay time (more than three), the influence of the number of buses and the moments of their arriving to the intersection on the delay time is observed (Fig. 5).

Correlation-regression analysis shows the adequacy of the model (2) to the obtained results of observations of the bus stops. Similarly, the adequacy of the model (3) is confirmed both for individual cycles (Fig. 6) and on average based on generalized results (Fig. 7).

For each specific cycle of traffic light regulation, the logarithmic (exponential) form of the dependence is confirmed. For the entire data set for buses that passed through the intersection in one observation, the exponential form of the dependence is also confirmed with a correlation coefficient of 0.72.

The earlier the first bus arrived relative to the start of the green time and the greater the number of these buses, the higher the accumulated delay time will be. When calculating this indicator, the first bus that arrives and stops has the highest weight, since it sets a high initial

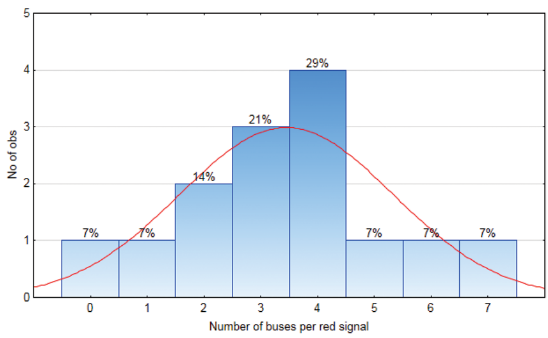

Figure 4: Distribution of the number of buses stopped at a red traffic light per traffic light control cycle.

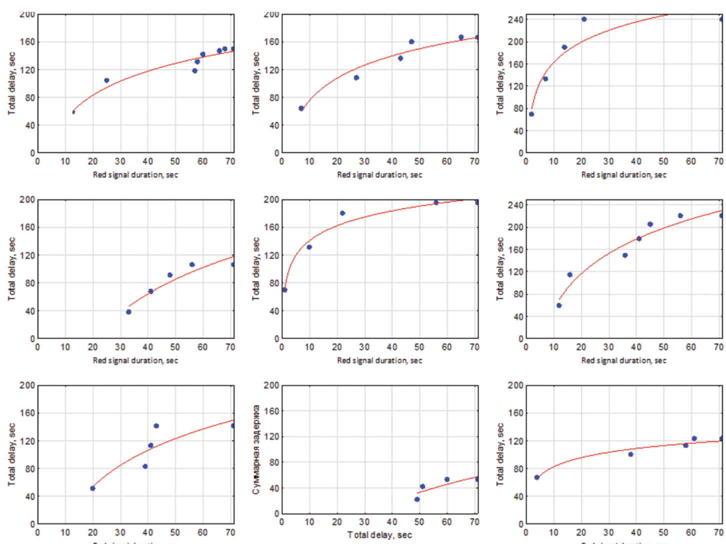

Figure 5: Stopping times and total delay values obtained from observation.

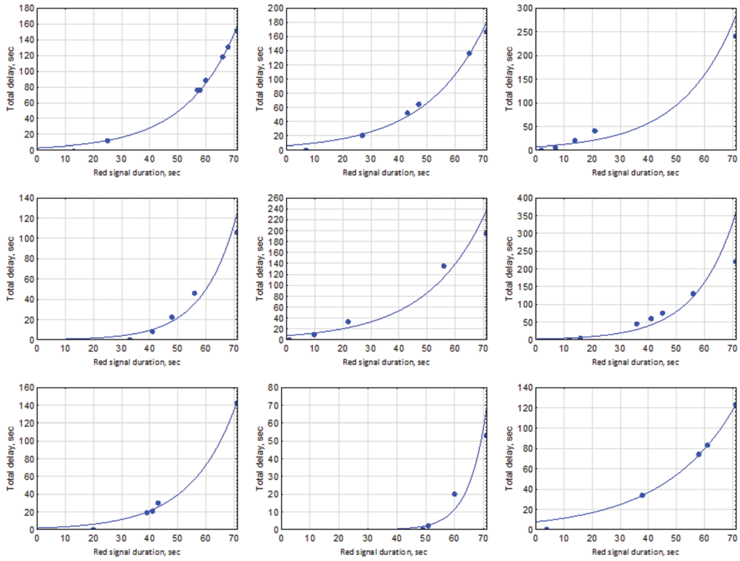

Figure 6: Values of stopping times and total time by cumulative delay effect obtained from observation.

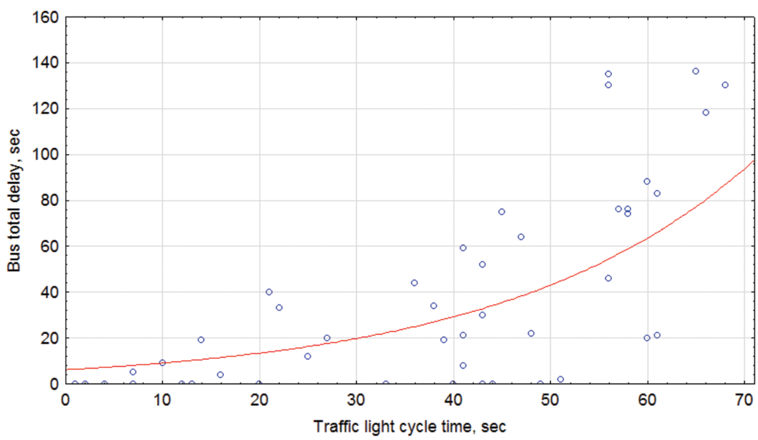

Figure 7: Stopping times and total delay values from observation.

value for the delay. If priority is given to the movement of this bus, it is possible to significantly reduce the accumulated standing delay time during the period of the green time.

If the well-known green extension method to 12 s is applied to the object, then the delay time would decrease by 1,176 s/h (32.3%). Using the 12-s stage recall, the effect would be 1,184 s/h (32.5%), i.e. the effect for buses from the use of both methods is the same. However, it is necessary to understand what time losses other road users will suffer. For this, simulation modelling was used in the work.

With an increase in traffic intensity in all six variants, the bus delay time in the model increases. The largest increase in the delay time with increasing traffic intensity is observed in the scenario without using PTP. The smallest influence of traffic volume on bus delay time is observed in scenarios using combined priority options (active + passive). The maximum reduction in the buses delay time relative to the basic variant is observed in the combined method (bus line + "stage recall"). Considering the slope of the trend lines to the abscissa axis, it can be concluded that each PTP method is sensitive to changes in traffic intensity at the intersection. At low traffic volumes, the delay time varies from 36.6 to 40.8 s (11.3%) when using different PTP methods (Fig. 8). At high flow, the delay time varies from 40.3 to 78.0 s (93.6%).

Combined priority options (active + passive) have the least sensitivity to changes in traffic intensity. The difference between the delay time at high and low traffic intensity is 9% (bus line + "stage recall") and 11.5% (bus line + "green extension"). Of the two active priority modes, the "green extension" has a higher sensitivity to traffic intensity. Increase in the delay time with increasing traffic intensity from 40.0 (1,600 vehicles/h) to 70.2 (2,060 vehicles/h) s (75.6%). Similar results were obtained for the vehicles delay time (Table 2).

At low traffic volumes, the delay time for personal transport varies from 36.8 to 39.2 s (6.4%) when using different priority methods (Fig. 9). At high traffic flow, the delay time varies from 128.7 to 238.0 s (84.9%).

Combined priority options (active + passive) are most sensitive to changes in flow rate. The difference between the delay time at high and low flow rates is 508.0% (bus lane + "Stage recall") and 519.2% (bus lane + "green extension"). Of the two active priority modes, "green extension" has a lower sensitivity to flow rate. Delay time increases with increasing flow rate from 36.9 (1,600 vehicles/h) to 133.3 (2,060 vehicles/h) s (261.4%). It should be noted that without PTP, with an increase in flow rate, the delay time for cars increases by 249.8% (from 36.8 to 128.7 s).

The least negative impact on the movement of personal transport is observed when using "green extension". With a flow rate of 1,990 vehicles/h, the delay time for vehicles using this control method increases by 27.6% compared to the basic option. In comparison, the use of a bus lane results in an 84.3% increase in car delays at the same flow rate. The use of "stage

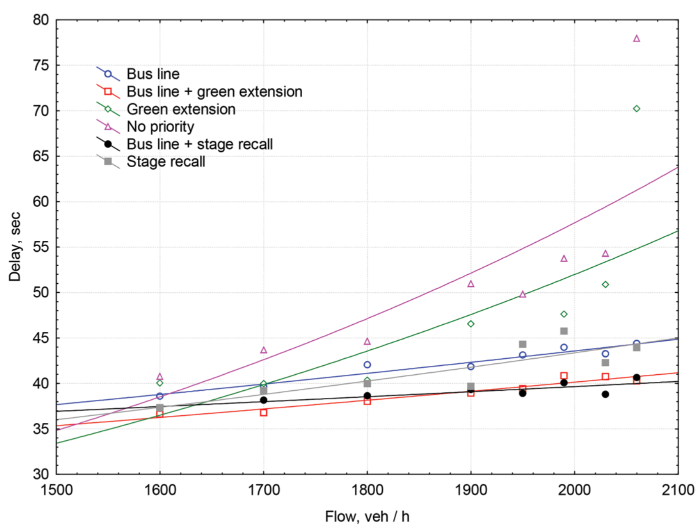

Figure 8: Influence of flow rate on bus delays when using different PTP methods.

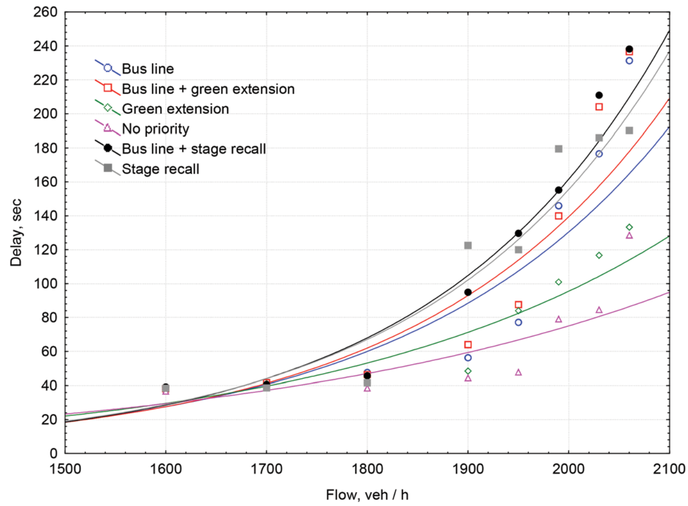

Figure 9: Influence of flow rate on car delays when using different PTP methods.

recall" has a more significant effect on the movement of personal vehicles (an increase in delay of 126.7% with a flow rate of 1,990 vehicles/h) compared to the bus lane or combined options.

The "stage recall" algorithm is more aggressive towards traffic. There is an increase in the number of algorithm triggers at a high bus flow rate (Fig. 10). The higher the bus flow rate, the more often the active priority system is triggered. With an increase in the number of triggers, the speed of buses and cars in the same direction increases. However, the speed of cars in the secondary direction is significantly reduced due to the more frequent reduction in the duration of the permitting signal of the traffic lights.

With an increase in bus flow rate from 10 to 120 vehicles/h, the number of algorithm triggers increases (triggering occurs in each traffic light control cycle). There is a decrease in the speed of cars in the secondary direction (from 27.9 to 5.9 km/h) and a slight increase in the speed of cars in the main direction (from 39.8 to 46.5 km/h). Because of this, the delay time increases significantly. It is advisable to evaluate not only the average delay time separately for individual and public transport, depending on the number of vehicles, but the total delay time, taking into account the average number of passengers in the vehicle. The final delay time is determined by the sum of the time lost by drivers and passengers in the *i*-th vehicle of the *j*-th type.

$$T_d = \sum_{i=1}^{n} T_{di} = \frac{t_{di} \cdot Q_{di}}{3{,}600} = \frac{t_{di} \cdot q_i \cdot N_i}{3{,}600}, \tag{6}$$

where T_d – total delay time per hour of academic time, h/1 h; T_{di} – total delay time of the *i*-th mode of transport, h; t_{di} – average delay time of the *i*-th mode of transport, s/person; Q_i – number of passengers carried by the *i*-th mode of transport on a section of the road network, people/1h; q_i – average number of passengers in one vehicle of the *i*th mode of transport, people/vehicle; N_i – traffic intensity of the *i*-th type of transport, vehicle/1 h: *i* – serial number on the general list of modes of transport; *n* – the number of modes of transport on the general list.

Two-factor dependences of the final delay time on the traffic intensity of personal and public transport are presented as surfaces in Figs. 11–13.

With an increase in flow rate, the delay time increases. The growth rate with a small number of buses (40 vehicles/h) increases significantly with a flow rate of more than 1,750 vehicles/h. With a higher bus flow rate (from 80 to 120 vehicles/h), the bus lane has a significant effect on reducing the delay time. With a flow rate of more than 1,750 vehicles/h, the use of a bus lane leads to an increase in the delay relative to the basic option for any number of buses. In this case, more people are moving in cars than on public transport. Under these conditions, we should consider methods of providing active priority of bus passage.

The use of the "green extension" algorithm reduces the delay time at a high car flow rate (1,900 vehicles/h) and a small number of buses (40 vehicles/h). Under these conditions, the delay time is 51.6 h, which is 3% less compared to the basic option and significantly less than with the bus lane option. With a large number of buses (120 vehicles/h) and a car flow rate

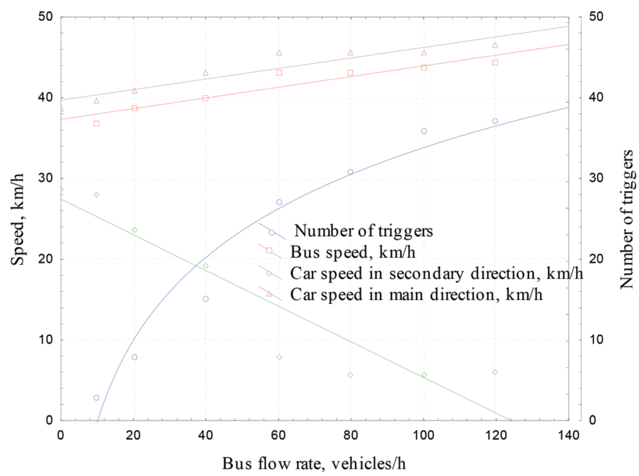

Figure 10: Changes in vehicle speed when applying the stage recall turn-on algorithm.

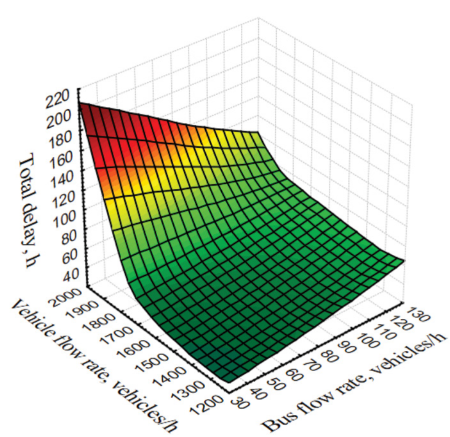

Figure 11: Total delay time for the bus lane method with 30 passengers on the bus.

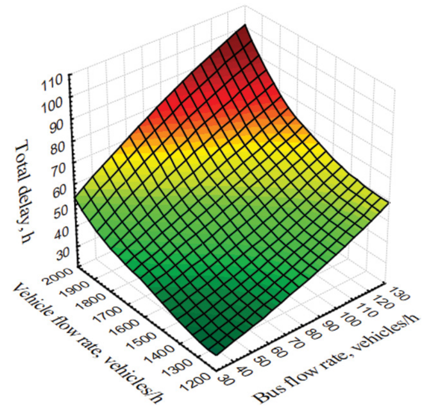

Figure 12: Total delay time for the “green extension” method with 30 passengers on the bus.

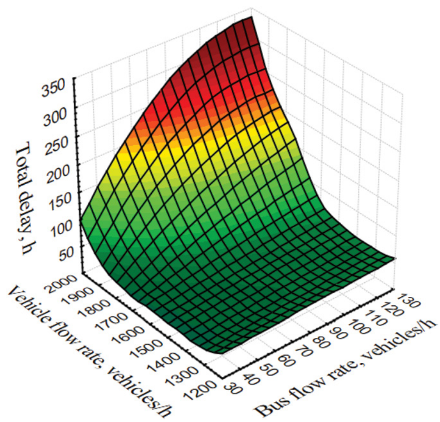

Figure 13: Total delay time for the “stage recall” method with 30 passengers on the bus.

of 1,900 vehicles/h, the delay time is 85.8 h, so this method does not give a significant effect compared to the basic option (86.2 h).

Along with the “green extension” algorithm, the “stage recall” bus priority algorithm is actively used. When applying the “stage recall” algorithm at maximum flow rates of cars and buses, the delay time increases significantly.

With a car flow rate of 1,900 vehicles/h and a bus flow rate of 120 vehicles/h, the delay time increases by 178% relative to the basic option. With a car flow rate of 1,300 vehicles/h and a bus flow rate of 40 vehicles/h, a decrease in the total delay time by 4% relative to the base case is observed, and with a bus flow rate of 120 vehicles/h—by 12%. The area of rational use of this control method is in the area of a high bus flow rate and a low car flow rate.

4 DISCUSSION

The combined consideration of vehicle traffic and the number of passengers makes it possible to determine the area of rational use for each technology of active PTP. The combination of the best ways to give PTP with different combinations of traffic intensity made it possible to form the area of their rational use (Table 1).

Table 1: The area of rational use of technology with 30 passengers per bus.

Bus flow, vehicles/h	Relative changes in total delay time when using the optimal priority method with the car flow rate, vehicles/h				
	1.300	1.450	1.600	1.750	1,900
40	–6%	–5%	–4%	0%	–3%
60	–7%	–6%	–2%	–1%	–1%
80	–6%	–5%	–7%	–3%	0%
100	–8%	–7%	–7%	–4%	0%
120	–14%	–12%	–6%	–5%	0%

Note:

Color code	PTP method
(pink)	Green extension
(green)	Bus lane + Stage recall
(blue)	Bus lane + Green extension
(white)	No priority
(beige)	Bus lane

With a low car flow rate (1,300–1,600 vehicles/h) and a large number of buses (100–120 vehicles/h), the least delay time is achieved when using the combined option (bus lane + "stage recall"). When the bus flow rate decreases, the combined option with the bus lane and the "green extension" algorithm is more effective.

With high flow rates of cars and buses, the use of a bus lane and combined options becomes impractical due to the small number of bus passengers. With a bus flow of 40 vehicles/h (30 passengers per bus) and a car flow of 1,600 vehicles/h (1.5 passengers per car), the ratio of the number of users of the transport system is 33.3% for buses and 66.7% for cars. With a small number of buses and a car flow rate of 1,900 vehicles/h, the use of the active "green extension" priority leads to an insignificant effect of up to 3% relative to the basic option.

When developing PTP technologies, we must take into account not only the number of buses but also the number of passengers. With an increase in the number of passengers from 30 to 100 people per bus, relative changes in total delay time increase, and in some cases the optimal method for a specific set of conditions changes (Table 2).

With a large number of buses and a low flow rate, the most optimal is the combined method (bus lane + "stage recall"). With a small number of buses (40 vehicles/h), the combined option with a bus lane and the "green extension" algorithm is optimal. The same algorithm is advisable to use at high flow rates (1,750–1,900 vehicles/h) for any number of buses.

This example of building a rational use area takes into account only one specific value of the parameters of the bus lane and the active priority algorithm. Before developing measures to implement PTP on real city streets, the parameters of the bus lane and active priority algorithms in relation to specific conditions must be optimized.

Table 2: The area of rational use of technology with 100 passengers per bus.

Bus flow, vehicles/h	Relative changes in total delay time when using the optimal priority method with the car flow rate, vehicles/h				
	1.300	1.450	1.600	1.750	1,900
40	–12%	–10%	–11%	–2%	–7%
60	–13%	–12%	–8%	–5%	–6%
80	–11%	–9%	–14%	–11%	–8%
100	–14%	–13%	–18%	–10%	–4%
120	–20%	–18%	–17%	–10%	–13%

5 CONCLUSION

The use of a single PTP method on the entire street and during the day does not allow obtaining the greatest effect for certain periods of time and sections of streets. However, it simplifies and accelerates the decision-making process on its choice, implementation, and management. Differentiation of the methods for providing public transport priority in space and time minimizes loss of time for traffic for each section of the street and time period. This complicates the process of creating and managing the transport system. The concept of PTP, including by creating a priority for crossing intersections, should take into account the geographical features of the city, the level of development of road networks, the structure of transport mobility of the population, and other factors.

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