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Prioritization of urban public transport on streets with high pedestrian volumes

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Abstract. The paper investigates the improvement of methods of time-based prioritization of public transport buses on city routes, taking into account pedestrian traffic indicators. A method of non-stop passing the stop-lines at signalized intersections and pedestrian crosswalks by buses in places of high generation of pedestrian traffic has been developed. A study was conducted at three signalized intersections and pedestrian crosswalks in Lviv city in places of high generation of pedestrian flows with dedicated lanes for public transport. Pedestrian speed of movement while crossing the roadway in such locations was studied, and the value of the speed of movement of 15% of the pedestrian flow, which potentially will not have time to cross the roadway during the time of the activated permissive signal, was found. The time parameters of extending the restrictive signal for traffic flows for the safe and unobstructed passage of pedestrian flows at the traffic light object are defined. The distance at which public transport should be located from the signalized facility to extend the restrictive signal to public transport, is also determined.

1 Introduction

With the development of the automotive industry, the main attention on the urban road networks was paid to cars. Wide roadways were designed to allow more traffic, pedestrian crosswalks were arranged in inconvenient places for this, and bicycle lanes were not popular. The issue of sustainable development and sustainable mobility began to arise in the 90s of the last century. The author [1] emphasizes a paradigm shift in the field of road transport, where more attention is paid to alternative modes of movement, namely walking, cycling, public transport, etc. Such a change was the result of increasing volumes of environmental pollution by emissions of exhaust gases from cars, noise, which negatively affects the health of city residents, the growth of traffic jams on urban road networks, the increase in time spent on travelling to work and study by urban residents, and an increase in the number of traffic accidents. With the growth of motorization level on the road networks of cities, the realization has become that applying only engineering solutions, such as, for example, expanding the roadway to increase the number of traffic lanes for cars, will not solve the problems mentioned above.

Over the past 20 years, various countries have achieved various successes in creating comfortable traffic conditions for movement by alternative means of transport. Restrictions on the prohibition of movement by private cars in certain parts of cities are made, pedestrian zones, pedestrian and bicycle paths are arranged, time-based and spatial priority is given to public transport, etc.

Nevertheless, in many developing countries, measures to create safe and comfortable conditions for the movement of all categories of road users are not being developed and implemented at the same pace as in the developed countries of Europe, North America or Japan. The lack of regulatory documents that would regulate the provision of infrastructure for alternative means of transport and insufficient financing of engineering projects and solutions in cities lead to the fact that city residents do not want to move on foot, by bicycle or by public transport due to inconvenience or even danger. In Ukraine, cycling and pedestrian paths are also not always designed in compliance with the requirements for ensuring road safety. Namely, there is practically no time-based priority for public transport, and the number of allocated lanes for its movement is not enough, even though the State Building Regulations regulate the allocation of lanes for public transport, as well as bicycle and pedestrian paths [2]. In particular, this normative document states that all pedestrian crosswalks should be at the same level as the roadway to ensure convenient movement, in particular for groups with limited mobility. Arterial streets of city-wide importance with continuous traffic, entrances to subways, lines of high-speed trams or trains, and streets where such a need is determined by the features of the terrain can be exceptions. Therefore, it is relevant to study these measures to increase the efficiency, convenience and safety of the movement of persons who use alternative means of transport.

The issue of the interaction of pedestrian and bicycle flows with public transport in the places where the first cross the roadway requires a separate study since, by the principles of sustainable mobility, the priority is the

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improvement of public transport and the promotion of pedestrian and bicycle traffic, which includes ensuring safety for all road users [3].

2 Analysis of literary sources

In the literature, there are many works dedicated to the study of the movement of public transport and pedestrians. As for public transport, the main attention is focused on reducing delays in its movement when passing signalized intersections since such nodes are points of interaction of a large number of traffic and pedestrian flows. In particular, authors [4] developed a methodology for giving priority to buses using deep reinforcement learning at congested intersections, including public transport. Deep reinforcement learning is a branch of machine learning based on using neural networks. It deals with the study of what actions an "agent" (in this case, a traffic light controller) should perform in a certain environment (road network) to receive a "reward" (optimization of traffic or minimization of delays when setting priority for public transport). Reducing the waiting time for the traffic light permissive signal for buses and other traffic flow has been considered. A comparison was made of the efficiency of the movement of vehicles under the existing duration of the traffic light cycle (fixed-time control) and with the use of the deep reinforcement learning method. When developing the model, the movement of pedestrians at the studied intersection was taken into account, namely the maximum duration of the restrictive signal for pedestrians. However, it was not indicated whether the developed method improved the traffic conditions for pedestrians, that is, whether the delay while waiting for the traffic light signal was reduced.

Regarding the movement of pedestrian flows, most studies are focused on the safety of pedestrians crossing the roadway. Among the methods that increase the efficiency of unobstructed and safe passage of pedestrians through signalized pedestrian crosswalks, the authors [5, 6] indicate priority intervals for the priority passage of pedestrians moving in the same phase as vehicles turning to the right. However, while time intervals can only increase the safety of pedestrian traffic by minimizing the conflict with turning vehicles, the authors [6] emphasize reducing the duration of the traffic light cycle when also using spatial priority for pedestrians in the form of a widespread sidewalk before a pedestrian crosswalk. In this case, pedestrians begin to cross the road faster, while vehicles need more time to get from the stop line to the conflict zone with pedestrians. However, such measures are appropriate only when there is a conflict between pedestrian flows crossing the roadway and vehicles turning right in the same phase.

There are also works dedicated to studying traffic and pedestrian flow delays at signalized intersections of the road network. For example, in paper [7], research was conducted on optimizing the structure and duration of the traffic light cycle, taking into account the delays for various road users, namely the general traffic flow, public transport and pedestrians. Various scenarios were considered, namely the presence of coordination for traffic flows, different durations of the traffic light cycle, and the presence of a calling device for pedestrians or their priority passage in the case of simultaneous movement with turning vehicles. The assessing of the scenario consisted of the sum of the estimates of the delay of the general traffic flow, public transport, and pedestrians and the assessment of the stress threshold when pedestrians cross the roadway. However, in this case, priority passage of public transport was not considered. It is only noted that in the case of existing time-based or spatial priority, delays for public transport will be smaller. The results showed that the scenario with a similar distribution of preferences for all traffic participants is the most effective, as otherwise, there are delays for either traffic or pedestrian flows.

The authors [8] also study the delays of all road users but from the point of view of the optimal way for pedestrians to cross the roadway. At-grade signalized pedestrian crosswalks, pedestrian bridges and underground pedestrian crosswalks with the presence of escalators were considered. For this purpose, three scenarios have been developed. Namely, a study of the total delay for traffic and pedestrian flows, a study of the delay per passenger in vehicles in the flow, and a study of the delay per passenger, but a higher priority is given to those passengers who move in non-motorized transport and public transport. Delays were determined for three scenarios for the existing duration of the traffic light cycle and for its designed duration. It was determined that the most optimal way for pedestrians to cross the roadway is a signalized pedestrian crosswalk.

An important issue in the study of optimal modes of control of traffic light objects, taking into account pedestrians, is their behavior. It is known that the time which pedestrians are willing to wait patiently for the activation of the permissive signal is 30 seconds. After that, they start to cross the roadway in violation of traffic rules. For example, work [9] considered the issue of the optimal duration of a restrictive signal for pedestrians, taking into account their behavior and minimizing delays in traffic flows. Signalized pedestrian crosswalks were considered in three cases: in the central part of the city, near transport hubs and in a residential area. Based on this, the maximum durations of restrictive signals for pedestrians are determined, taking into account the volume-capacity ratio of traffic flows.

As for the study of the behavior of pedestrians when giving time priority to public transport, this issue is little researched. As noted by the authors [10], despite a large number of studies on reducing delays at signalized facilities for public transport in general and their passengers, as well as giving time-based priority to buses, there are practically no studies on the impact of giving this type of priority on pedestrian flows at signalized facilities. That is why the authors conducted a study of the delay of pedestrians and passengers at adjacent intersections with those where priority is given to public transport. The issue of the effect of extending the permissive signal of the traffic light for priority passage of public transport on delays in the movement of pedestrians and passengers of public transport at adjacent intersections for three options for the duration of the permissive signal was considered.

Several of studies have also been conducted [11-15] on the influence of pedestrian movement speed on the structure of the traffic light cycle or the determination of the optimal speed of pedestrian flow, which must be taken into account when calculating the duration of the traffic light cycle.

For example, the authors [11] studied the speed of pedestrians at different stages of crossing the roadway: at the beginning of the crosswalk, in the middle, and at the end; also at different stages of the traffic light phase: when the green, flashing green and red signal is on. Paper [12] investigated the speed of pedestrians moving in phase with right-turning vehicles. It has been determined that pedestrians moving more slowly create a kind of "tail" that causes delays to traffic planning to turn right.

The authors [13] investigate the average speed of the pedestrian flow, taking into account its heterogeneity, namely the presence of different age categories and sexes for different types of pedestrian crosswalks (unsignalized and signalized), as well as the presence of safety islands, which will allow crossing the roadway in two stages. It was determined that women, children and older people have the lowest speed of movement. The authors [14] also studied the speed of movement of the pedestrian flow with a high rate of older people when crossing the roadway at signalized objects. Having reached similar conclusions as the previous authors, they also determined the recommended speed of the pedestrian flow, which should be adopted when designing the traffic light cycle if the proportion of older pedestrians exceeds 15%.

According to the results of studies [15], the authors claim that, in general, the speed of movement of pedestrians when they cross the roadway has increased significantly over the last decade. Therefore, there is now a need to review the design solutions of pedestrian crosswalks to improve the pedestrian infrastructure, taking into account the speed of pedestrian traffic.

In general, despite the large number of studies on the speed of pedestrian flows at signalized intersections and pedestrian crosswalks, analyzing their influence on adaptive control has not been carried out.

3 Problem statement

In previous studies [16], we determined that for cities with a radial-ring scheme of road network planning, active time priority should be given to public transport on sections up to 200 m long, which actually corresponds to placement in the central parts of cities. However, as is known, the central part of the city is also a place of high concentration of pedestrian flows, which, among other things, cross the roadway at signalized and unsignalized pedestrian crosswalks. Therefore, the issue of their interaction without negative influence on each other is relevant.

The time required for pedestrians to cross the roadway is defined in the State Standard [17]. It is calculated:

$$t_{\text{ped}} = B_{\text{rw}} / V_{\text{ped}} + 5, \quad (1)$$

where t_{ped} – duration of the permissive signal for pedestrians, sec; B_{rw} – roadway width (when calculating the minimum permissive signal under adaptive control – the distance from the edge of the roadway to the safety island or marking line that separates traffic flows of opposite directions), m; V_{ped} – speed of movement of pedestrians when crossing the roadway, m/sec.

According to the standard [17], when calculating the duration of the permissive signal for pedestrians, the speed of their movement is assumed to be 1.3 m/sec. However, as is known, as the pedestrian flow volume increases, their speed decreases. Therefore, at pedestrian crosswalks with high values of pedestrian flow volumes, such a speed value may be irrelevant. In addition, there are different age groups and people with disabilities in the pedestrian flow, whose speed of movement may be lower.

It is necessary to set the minimum and maximum values of the permission signal for non-priority phases to give active priority to public transport. Taking into account the fact that with the radial and radial-ring planning schemes, the traffic volume in secondary directions is insignificant, the minimum time of the permissive signal for the non-priority direction will correspond to the duration of the pedestrian crossing of the roadway. Therefore, the presence of pedestrians who do not have time to cross the road can lead to emergencies, when the bus, which is in front of the stop-line, will be forced to brake to avoid hitting the pedestrian, even if the permissive signal is turned on for this vehicle.

Therefore, the purpose of the study is:
– to investigate the speed of movement of pedestrian flows when they cross the roadway in places of high generation of pedestrian correspondences;
– to determine the "critical" values of pedestrians speed of movement, at which they do not have time to cross the roadway;
– to determine the time by which it is necessary to increase the duration of the permissive signal for pedestrians to complete their maneuver safely;
– to determine the necessary distance at which the rolling stock of public transport is located in relation to the signalized facility within the range of the traffic detector. At this distance, it is necessary to extend the restrictive signal for this rolling stock for the safe passage of pedestrians.

4 Research results

Three traffic light facilities in the Lviv city were chosen for the study:
– traffic light facility #1: Svobody Ave. – Hnatiuka Str. intersection (in the direction to Svobody Ave. – Doroshenka Str. intersection);

– traffic light facility #2: Chornovola Ave. – Pid Dubom Str. intersection (in the direction to the center of the city);

– traffic light facility #3: signalized pedestrian crosswalk on Horodotska Str. (near trade center "Pryvokzanlyy" in the direction of the center of the city).

All facilities have an allocated lane for public transport, and there are places of pedestrian flow generation nearby, which causes high values of their volume at the studied objects. The number of traffic lanes at the intersection of Svobody Ave. – Hnatiuka Str. and the pedestrian crosswalk on Horodotska Str. – three in each direction; at the intersection of Chornovola Ave. – Pid Dubom Str. – two in each direction. The width of the traffic lane for all objects is 3.5 m. There are dividing lanes everywhere, and there are no public transport stops at the approach to the signalized facility.

Studies of the speed of pedestrian movement while crossing the roadway were carried out by measuring the time it took for a pedestrian to cross the roadway from the sidewalk to the safety island. The number of measurements is 100 for each pedestrian crosswalk. The pedestrian flow volume (N_{ped}) at each of the facilities is also determined. The results of the measurements are given in Table 1.

Table 1. The results of measuring the main indicators of the movement of pedestrian flows during their passage through the roadway.

Number of traffic light facility	N_{ped}, ped/h	Mathematical expectation (M_V), m/sec	Dispersion (D_V), m/sec
1	485	1,29	0,03
2	633	1,23	0,03
3	870	1,16	0,02

As expected, pedestrian traffic volume has an effect on the speed of movement of pedestrians. At the same time, the average value of these movement speeds is less than the 1.3 m/sec set in formula (1). Therefore, there is a high probability that some pedestrians will not have time to cross the roadway. The distribution of pedestrian speeds at each traffic light is shown in Fig. 1.

So, we can see that at traffic light facility #1, 15% of the pedestrian flow moves at a speed of less than 1.04 m/sec; at traffic light facility #2, this speed is 1.02 m/sec, and at traffic light facility #3 – 0.95 m/sec. On average, this value will be one m/sec. Therefore, we can say that pedestrians whose speed is less than one m/s will not have time to cross the roadway in time while the permissive signal is turned on for them.

Therefore, if the detectors detect pedestrians who remain on the roadway when the duration of the permissive signal expires at the approach of the public transport to the traffic light facility, it is necessary to extend the duration of this permissive signal, taking into account the fact that the speed of the pedestrian will be one m/sec. Therefore, this time will be:

$$t_{ped(add)} = B_{rw} / V_{ped}. \quad (2)$$

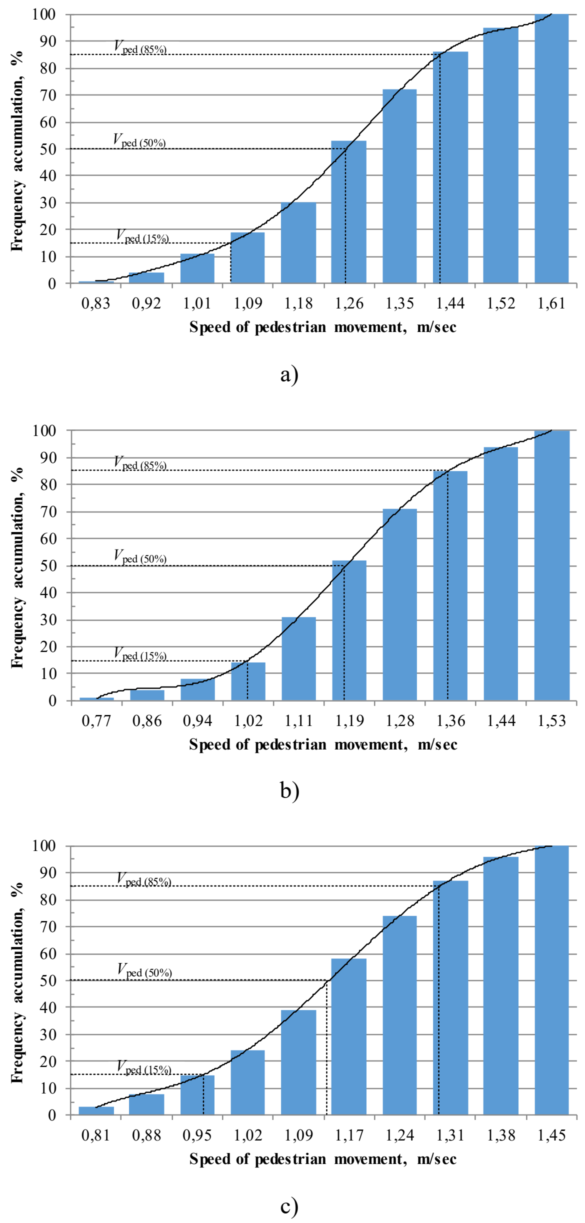

Fig. 1. Distribution of pedestrian movement speeds:
a) at traffic light facility #1; b) at traffic light facility #2; c) at traffic light facility #3.

Based on this, it is necessary to determine the distance at which public transport should be at the approach to the stop-line to extend the restrictive signal of the traffic light for this public transport (Fig. 2).

According to known physical formulas, the distance from the location of public transport to the traffic light is calculated as the product of the speed of the public transport and the time it takes to reach the traffic light:

$$L_{det} = t_{PT} \cdot V_{PT}. \quad (3)$$

Since we need to find the distance at which it is expedient to continue the restrictive signal of the traffic light for traffic, then $t_{PT} = t_{ped(add)}$. We will get:

$$L_{det} = (B_{rw} / V_{ped}) \cdot V_{PT}. \quad (4)$$

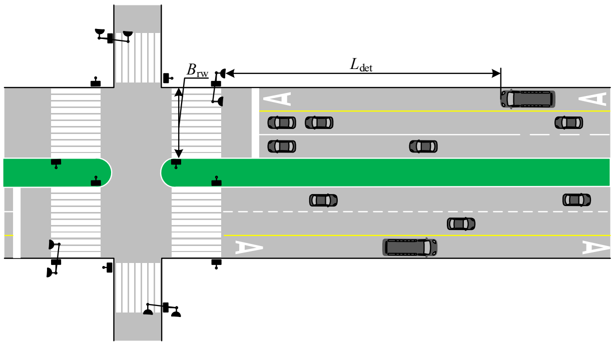

Fig. 2. Scheme of location of public transport at the approach to the stop-line, to determine the distance required for the continuation of the restrictive signal.

Considering that we take $V_{ped} = 1$ m/sec, we will get:

$$L_{det} = B_{rw} \cdot V_{PT}. \quad (5)$$

So, if:

$$L_{det} \leq B_{rw} \cdot V_{PT}, \quad (6)$$

then the restrictive signal of the traffic light for public transport should be extended to:

$$t_{ped(add)} = B_{rw} / V_{ped}. \quad (7)$$

If:

$$L_{det} > B_{rw} \cdot V_{PT}, \quad (8)$$

then at the moment when public transport approaches the stop-line, pedestrians will have time to cross the roadway, so there is no need to increase the duration of the restrictive signal.

In further studies, it is necessary to test this hypothesis with the help of traffic simulations.

5 Conclusions

In this paper, a study of the speed of movement of pedestrian flows when they cross the roadway at signalized intersections or pedestrian crosswalks is carried out. Measurements were carried out at three signalized facilities with similar characteristics in places of high generation of pedestrian traffic. We have determined that 15% of the pedestrian flow moves at a speed of less than one m/s. Therefore, this group of pedestrians will potentially not have time to cross the roadway during the permissive traffic light signal, which may cause conflict situation with vehicles that should start moving in the next phase. Special attention should be paid to public transport, for which spatial priority is arranged as an allocated lane for their movement and time-based active priority.

Therefore, the time for which it is necessary to extend the restrictive signal of the traffic light for traffic is determined so that pedestrians who do not have time to cross the roadway can complete their movement.

The distance at which public transport should be located to the traffic light facility for the restrictive signal of the traffic light to be extended for the unhindered passage of pedestrians is also determined. If the public transport is at a larger distance than the specified one, the continuation of the restrictive signal of the traffic light for traffic will not affect the efficiency of the functioning of the public transport.

Further research will be aimed at determining the impact of the extension of the restrictive signal for public transport on its movement at different values of the public transport volume.

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