IMPROVING THE METHODOLOGY OF ADAPTIVE TRAFFIC CONTROL AT PEDESTRIAN CROSSWALKS

Yuriy Royko, Oleh Hrytsun, Romana Bura*, Roman Rohalskyi, Yurii Yevchuk

Department of Transport Technologies, Lviv Polytechnic National University, Lviv, Ukraine

*E-mail of corresponding author: romana.r.bura@lpnu.ua

Yuriy Royko 0000-0003-0055-9413, Oleh Hrytsun 0000-0001-8391-9642,
Romana Bura 0000-0003-1027-8367, Roman Rohalskyi 0000-0001-8223-2320,
Yurii Yevchuk 0000-0002-8705-3791

Resume

The paper presents the results of an experimental study carried out at signalized intersections and pedestrian crosswalks in Lviv (Ukraine). The study covered intersections with different traffic conditions. Therefore, the intersections were classified into three types. It was found that the share of pedestrians who cross the road on the prohibitive traffic signal varies from 7% in the central areas to 13% near transport hubs. A methodology, which predicts the pedestrian behavior when they make decisions about crossing the roadway, is proposed. Recommendations were developed for choosing the optimal traffic light control modes. It was found that increasing the duration of the restrictive signal for pedestrians increases the probability of crossing the road during the restrictive signal of the traffic light. It emphasizes the need to adjust the duration of the traffic light cycle in areas with heavy pedestrian traffic.

Available online: https://doi.org/10.26552/com.C.2025.037

Article info

Received 8 November 2024
Accepted 26 March 2025
Online 12 May 2025

Keywords:

traffic flow
pedestrian flow
signalized pedestrian crosswalk
traffic light cycle duration
traffic delay

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Traffic delays on the road network are one of the main problems of modern cities, leading to time loss, environmental pollution, and excessive fuel consumption. This problem is exacerbated by the constant growth in the number of vehicles and the inefficiency of traffic management [1]. Traffic lights that control traffic at intersections should ensure a balance of traffic and pedestrian flow without increasing the waiting times, queues, and traffic density [2]. However, due to irrational signaling, traffic lights sometimes become bottlenecks in the road network.

Most traffic lights operate in modes with a predefined duration or using detectors. Control with a predefined duration uses fixed intervals of the permissive signals, while control with detectors adapts the phases depending on the detection of vehicles and/or pedestrians [3]. However, due to the high uncertainty in the arrival of vehicles and pedestrians, it is difficult to determine the long-term optimal values of the phases or their extension. As a result, this can lead to queues and excessive stops due to irrationally configured signals of traffic lights.

The latest technologies, such as adaptive traffic management systems, can be used to solve this problem. These systems can analyze data in real-time, predict changes in traffic volumes, and automatically adjust traffic lights to optimize the traffic and pedestrian flow [4]. Using detectors and cameras to collect flow data can also help to create more efficient and flexible control systems.

2 Literature review

Pedestrian crosswalks are one of the most dangerous places on the road network. Most road traffic accidents occur here. In urban centers, pedestrians crossing the road significantly impact the traffic flow. For this reason, several approaches have been developed to detect traffic and pedestrian flows before traffic lights [5-7]. In general, pedestrians should be given priority for various reasons. However, as emphasized in [8], the high priority for pedestrians at pedestrian crosswalks significantly affects the road network's capacity. The researchers evaluated different distances between pedestrian crosswalks, considering their variable nature.

The analysis in [9] shows that increasing number of pedestrians use mobile phones daily. It distracts them when they are getting ready to cross the roadway. Research [10] points to pedestrians as one of the most dangerous road users, with the highest probability of severe or fatal injuries in road accidents. That is why, there is a need to introduce new adaptive traffic control systems at pedestrian crosswalks, which are crucial for improving the pedestrian safety [11].

In [12], an algorithm for detecting traffic lights and pedestrian crosswalks was developed that successfully operates on embedded devices with limited computing resources in real time. This approach is based on image processing and is characterized by high recognition accuracy, although the quality of the results obtained may depend on the quality of the input images.

A high-resolution video surveillance system that collects vehicle and pedestrian traffic data at intersections is presented in paper [13]. This solution is characterized by high accuracy and the ability to collect essential data necessary to maintain safety and mobility in an urban environment.

Such systems are becoming an important component of modern adaptive traffic management systems. However, they do not consider the number of pedestrians waiting at the crosswalk [14].

For example, detectors to detect pedestrians on sidewalks and signalized crosswalks is proposed to use in [15]. Using detectors on sidewalks is challenging because it is crucial to ensure the correct shape and size of the pedestrian detection area. It is essential to identify pedestrians standing along the edge of the sidewalk, where an oval shape may be acceptable, as well as those approaching or standing on the approaches to the sidewalk.

To achieve this, more sophisticated detectors can be used to adapt the shape and size of the detection zone to suit specific conditions. It can be implemented using two beams directed at the pedestrian waiting area [16-18]. The first beam passes along the edge of the sidewalk, and the second beam is perpendicular to the road, covering the approach area. This allows to create a detection zone that better meets the needs of use on sidewalks.

This principle of operation allows the detectors to detect pedestrians both in the crossing area (detectors at the intersection) and in the waiting area on the sidewalk (detectors on the curb). Detectors placed on the sidewalk can track the presence of pedestrians and cancel crossing requests if a pedestrian has already started crossing the roadway [19]. This helps to avoid unnecessary delays and increases pedestrian safety [20].

In addition, particular detectors are used at crosswalks that automatically adjust the duration of the pedestrian phase. This allows sufficient time for safe crossing, especially when many pedestrians move slowly [21-23]. Using such detectors optimizes traffic lights' operation and increases pedestrian traffic efficiency and safety.

This configuration provides more accurate detection of pedestrians on the edge of the sidewalk and in the approach zone, significantly increasing the traffic safety and efficiency. This approach minimizes waiting time for pedestrians, providing them with comfortable road crossing conditions. In addition, using such systems helps to reduce the number of accidents, as drivers receive more accurate data on the presence of pedestrians at the crosswalk [24-25].

In [26], an algorithm for the traffic control at a signalized intersection using fuzzy logic was developed. This algorithm allows reducing the delay of traffic and pedestrian flows by adapting the parameters of traffic light control to traffic and pedestrian flows` volumes.

This study is aimed at determining the indicators or features of traffic flows and pedestrian behavior to substantiate the methodology for adaptive traffic control at pedestrian crosswalks.

It is necessary to perform the following tasks to achieve the objective of the work:

- to analyze the patterns and the main methods of studying the indicators of road users used to adjust the modes and parameters of traffic signal control systems;
- to conduct field studies of road users and analyze the behavioral characteristics of pedestrians at different types of intersections with traffic lights;
- to substantiate the mode of adaptive traffic control at pedestrian crosswalks, taking into account the characteristics of traffic flows and pedestrian behavior based on fuzzy logic;
- to develop recommendations for selecting the effective traffic signal control modes for different types of signalized intersections.

3 Materials and methods

Following the research objective, a number of measurements were made on the streets of Lviv (Ukraine) using the technical means of traffic management of the Lviv municipal enterprise “Lvivavtodor”. The experimental study was conducted at signalized intersections and a signalized pedestrian crosswalk outside the intersection (Figure 1). Active motion detectors for both vehicles and pedestrians were used for this study.

During the measurements, the following indicators were determined: width of the pedestrian crosswalk (B_{ped}), length of pedestrian crosswalks (street width, B_{rw}); actual traffic flow volume through the crosswalk (N_a), pedestrian flow volume (N_{ped}), the duration of the traffic signal control cycle at intersections and pedestrian crosswalks and its components (duration of restrictive and permissive signals); the number of pedestrians gathered before the crosswalk; the number of people who crossed the roadway during the restrictive (t_r) and permissive (t_p) traffic signal.

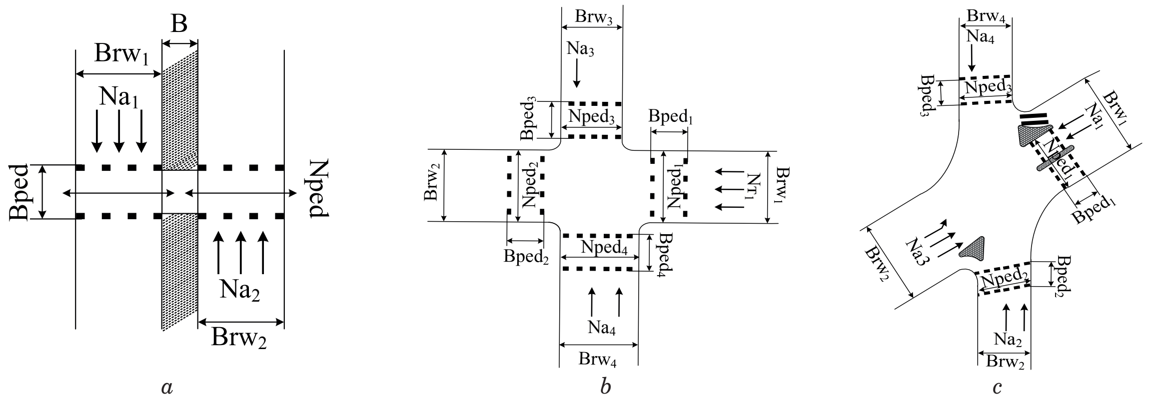


Figure 1 *Situational schemes of formation of the traffic and pedestrian flows, where experimental measurements were carried out: a - signalized crosswalk of type I (signalized pedestrian crosswalk with a dividing traffic lane); b - signalized crosswalks of type II (four-way intersection with four pedestrian crosswalks); c - signalized crosswalks of type III (combined four-way intersection with three pedestrian crosswalks)*

Table 1 *Types of intersections and pedestrian crosswalks in terms of their location in the city*

Type of intersection	Location on the territory of the city	Features of pedestrian flows	Features of traffic flows	Availability of a flow generation center
I	Near transportation hubs	Constantly intense during the peak periods; targeted towards and away from generation centers	High heterogeneity of traffic flow (up to 70% of passenger cars); a significant share of freight traffic and urban public transport, maneuverability in parking lots	Shopping centers, bus and train stations
II	Central zone	Constantly intense throughout the day	Significant homogeneity of the traffic flow (up to 95% of passenger cars)	The distribution of pedestrian flows across the territory is uniform
III	Residential area	Variable, unidirectional in the entire zone	The share of passenger cars is 80 - 85%, urban public transport - up to 10%; freight traffic is practically absent	Stopping points of urban public transport

During the research, the effectiveness and adequacy of the proposed solutions for the traffic control at pedestrian crosswalks was evaluated. This evaluation included checking how well the new control systems can control pedestrian and vehicular traffic, ensuring safety and convenience for all road users.

All these crosswalks can be conditionally divided into three types, depending on their location in the city (Table 1).

The research was conducted during the day in good weather conditions. The study tested several working hypotheses:

1. Different types of intersections and pedestrian traffic conditions require different durations of traffic signals to meet the needs of pedestrians to improve traffic safety.
2. As the traffic volume and length of the crosswalk decrease, pedestrians are more likely to try to cross the roadway when the traffic light is red.
3. The purpose of pedestrian movement can influence pedestrian behavior, changing their decisions about crossing the roadway.

This will provide more accurate information about the impact of different conditions on pedestrian behavior and the effectiveness of traffic management systems.

The sample size for traffic and pedestrian flow, required to ensure the representativeness of the data, was determined following the methodology outlined in [27]:

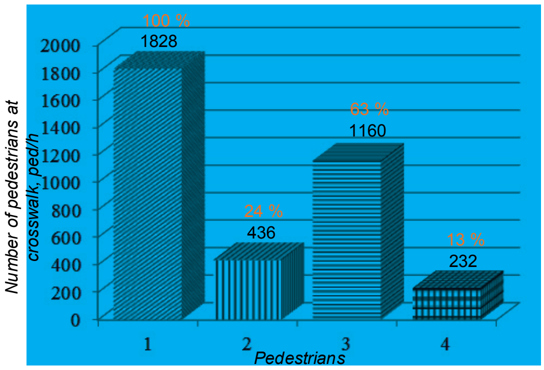
$$n = \frac{Z^2 \cdot p \cdot (1-p)}{E^2}, \tag{1}$$

where n - necessary sample size for traffic and pedestrian flow; Z - value for the selected significance level (1.96 is taken for 95%); p - the expected proportion (0.5 is assumed if there is no previous measurement data); E - is the permissible error (0.05 is taken).

Based on the calculations, the minimum number of situational interactions between the traffic and pedestrian flows, to be conducted at each type of intersection (crosswalk) to ensure a representative sample, was determined:

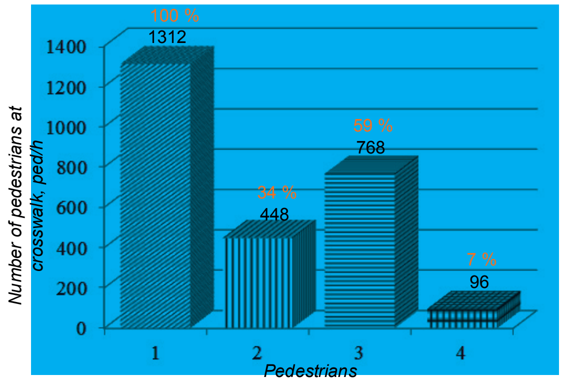
$$n = \frac{1.96^2 \cdot 0.5 \cdot (1-0.5)}{0.05^2} = \\ = 384.16 \approx 385\, interactions. \tag{2}$$

During the study, various parameters were analyzed



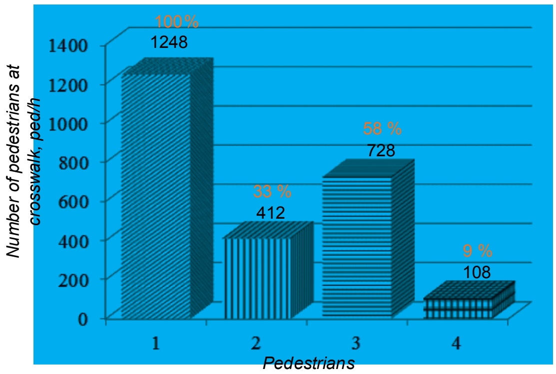
t_p = 25 sec; t_r = 47 sec; B_{rw} = 24 *m*; N_a = 1695 *auto/h*.

a)



t_p = 32 sec; t_r = 28 sec; B_{rw} = 12.1 *m*; N_a = 1365 *auto/h*.

b)



t_p = 32 sec; t_r = 28 sec; B_{rw} = 12.1 *m*; N_a = 1254 *auto/h*.

c)

Figure 2 *Results of pedestrian flow studies: a - signalized crosswalk of type I; b - signalized crosswalks of type II; c - signalized crosswalks of type III; 1 - the total number of pedestrians who crossed the crosswalk (on the restrictive and permissive traffic signal) and those who were waiting for the permissive traffic signal; 2 - pedestrians who were waiting for a permissive signal; 3 - pedestrians who crossed the crosswalk on a permissive signal; 4 - pedestrians who have crossed the crosswalk on a restrictive signal*

using video recordings made at the study sites, including vehicle and pedestrian characteristics, duration of the traffic signal for vehicles and pedestrians, geometric parameters of the road network, duration of the traffic light cycle, duration of pedestrian crossing, etc.

The graphical results of the study of pedestrian behavior at signalized crosswalks are shown in Figure 2.

Based on the results of the analysis presented in Figure 2, it was possible to confirm the working hypothesis 3. In particular, it was found that the share of people who violate traffic rules at signalized pedestrian crosswalks is 9% in residential areas. In the city's central areas (type II), this indicator is somewhat lower - 7%, while near the transport hubs (type I) it is up to 13%. The working hypotheses 1 and 2 were confirmed as well: to improve traffic safety at different types of intersections, traffic lights appropriate for pedestrian traffic should be used, as pedestrians are more likely to ignore the restrictive signals when the traffic volume and crossing lengths decrease.

Based on the results of these studies and previous ones, it can be concluded that the regulatory approaches to the arrangement of pedestrian crosswalks and the design of traffic control modes should consider the specifics of different types of intersections and pedestrian traffic conditions. These differences are determined primarily by the behavior of pedestrians at junctions, which depends on their psychophysiological characteristics and the purpose of their movement.

Therefore, to ensure the safety and efficiency of pedestrian traffic, it is necessary to develop adaptive and flexible solutions for different types of intersections. This includes planning crosswalks and managing the traffic signal control modes, which must be customized to specific conditions and behavioral patterns.

Thus, a more individualized approach to designing pedestrian crosswalks and controlling pedestrian flows would help to improve overall safety and comfort for all road users.

4 Results of theoretical and experimental studies

For effective planning of signalized pedestrian crosswalks on the road network, it is necessary to study and simulate traffic flows and pay due attention to pedestrian flows. It is essential to analyze pedestrian behavior depending on the roadway's geometric parameters and the crosswalk's location.

When developing a methodology for adaptive traffic control at pedestrian crosswalks, it is necessary to consider not only the psychophysiological and physical capabilities of people, but to predict the behavior of pedestrians when making complex decisions, as well. One of the main psychophysiological factors is the natural tendency of people to save effort and time by choosing the shortest route between destinations.

Predicting pedestrian behavior allows to adapt infrastructure and controls to minimize risks and ensure safer crossing in different traffic conditions. Figure 3 shows a block diagram of the automated traffic control system at a controlled crosswalk considering pedestrian behavior.

The main point of the above scheme is that intersections are equipped with an automated traffic control system (vehicle detectors), which takes into account fixed-time conditions (planning and geometric parameters of the roadway) and variable conditions (characteristics of traffic flows, road, and climatic conditions, and the number of waiting pedestrians).

As shown in Figure 3, the input variable in the proposed system is a group of pedestrians standing before the traffic light and preparing to cross the road.

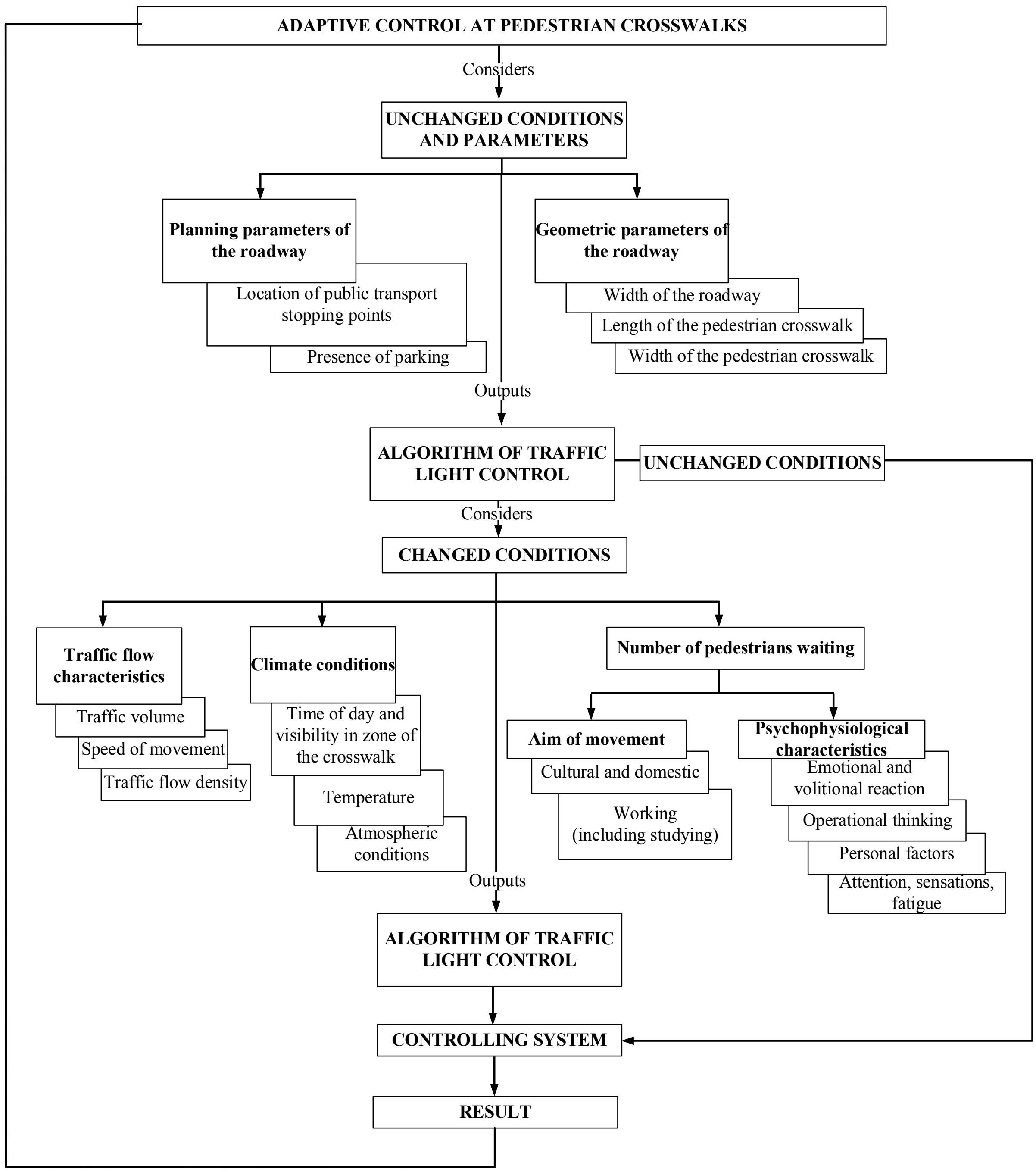


Figure 3 *Block diagram of adaptive traffic control at a controlled crosswalk considering pedestrian behavior*

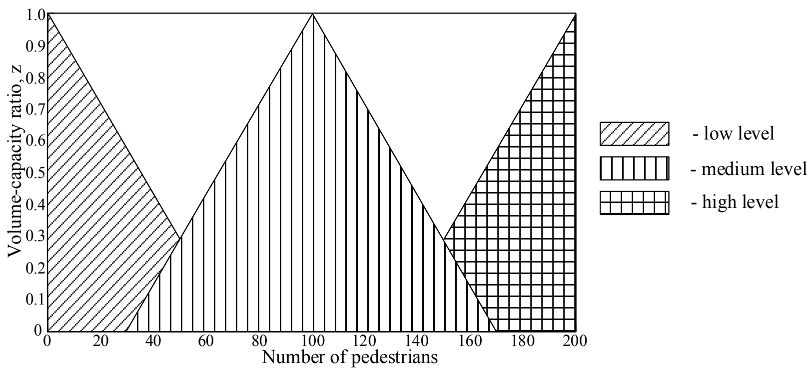


Figure 4 *Triangular membership functions for the number of pedestrians*

Table 2 *Recommendations for selecting the rational traffic signal control modes depending on the traffic delays and pedestrian behavior*

Volume-capacity ratio, z	Recommended duration of traffic light cycle, sec		
	Type of intersection I	Type of intersection II	Type of intersection III
	2 phases		
$z < 0.2$	adaptive	adaptive	adaptive
$0.2 \leq z \leq 0.45$	25 - 40	adaptive	adaptive
$0.45 \leq z \leq 0.7$	30 - 50	40 - 60	40 - 60
$0.7 \leq z \leq 1.0$	40 - 60	45 - 70	50 - 70
	3 phases		
$z < 0.2$	adaptive	adaptive	adaptive
$0.2 \leq z \leq 0.45$	40 - 60	50 - 70	50 - 70
$0.45 \leq z \leq 0.7$	50 - 70	60 - 80	60 - 80
$0.7 \leq z \leq 1.0$	60 - 90	60 - 90	60 - 90
	4 phases		
$z < 0.2$	adaptive	adaptive	adaptive
$0.2 \leq z \leq 0.45$	60 - 80	60 - 90	60 - 90
$0.45 \leq z \leq 0.7$	80 - 90	90 - 100	80 - 100
$0.7 \leq z \leq 1.0$	90 - 100	100 - 110	100 - 120

Various methods can be used to identify and count the size of a group, allowing to detect both static and moving groups of people.

To provide a correct input value for adaptive traffic control at pedestrian crosswalks, this paper uses a methodology based on using pedestrian counting detectors, which allows for an accurate assessment of the number of people in the area before the traffic light.

After describing the proposed scheme of an adaptive traffic control at a controlled crosswalk, it is advisable to focus on the aspects of fuzziness of the inference system that determines the phases of traffic lights. In particular, it is crucial to characterize the membership functions used in this system briefly.

The proposed detector, which includes a fuzzy logic controller, uses three basic membership functions to process the input data and control the output. These functions represent the three levels of volume:

- low level: the membership function corresponds to a small number of pedestrians, which reduces the time of the green phase of the traffic light;
- medium level: the membership function adjusts the time of the green phase of the traffic light accordingly based on the moderate number of pedestrians;
- high level: the membership function provides a longer green phase time for a large number of pedestrians waiting to cross the road.

The controller's input data relating to the number of pedestrians is distributed over these membership functions, with the range of pedestrian counts ranging from 0 to 200.

These membership functions are applied to the traffic light cycles (green, amber, and red) for the traffic light control. The controller output values are directly related to the setting of the duration of each traffic light cycle and of each traffic light phase. This allows adapting the time of green, amber, and red lights to the actual situation on the road, including the number of pedestrians waiting to cross.

The triangular membership functions for the number of pedestrians are shown in Figure 4, where the road network's volume-capacity ratio (z) is expressed by normalized values in the range from 0 to 1. This allows to clearly define how a specific value of the number of pedestrians affects the control of the traffic light. As for the time of day, unlike the number of pedestrians, obtaining a continuous numerical range is impossible. Instead, the time of day is divided into peak periods (07:00 - 09:00; 13:00 - 14:00; 17:00 - 18:00) and off-peak periods, which have different effects on the level of traffic on the road network.

Thus, recommendations are proposed for choosing the rational traffic signal control modes depending on the traffic delays and pedestrian behavior (Table 2).

The adequacy of these recommendations is checked next. It is taken, for example, a signalized crosswalk of type I (two-phase control). The width of the roadway is 24 m (11.25 m in each direction and a 1.5 m wide dividing lane). The total traffic volume at the crosswalk is 1695 veh/h (volume-capacity ratio - 0.35). Based on the fact that a large share of violators (13%) is observed at the studied facility under existing traffic conditions with a traffic light cycle duration of 78 seconds, it is possible to implement the traffic signal control for intersections of type I with a traffic light cycle duration of 25-40 seconds. For such traffic conditions at intersections of type II and III, it is necessary to implement adaptive traffic control since, in a fixed-time mode, there will be a large share of pedestrians crossing the roadway when the traffic signal is red.

For the two-phase control for intersections of type I with a road-capacity ratio of 0.35, the total cycle time of the traffic signal can be from 25 sec (7 sec green, 13 sec red, and 5 sec amber) to 40 sec (22 sec green, 13 sec red, and 5 sec amber). This cycle of 25 to 40 seconds is the basic cycle for a traffic light and is not an input or output parameter of a fuzzy logic controller.

The output of the fuzzy logic controller detects variations in these parameters, increasing or decreasing the duration of the green and red traffic lights according to the existing volume-capacity ratio on the road network. Pedestrian phases are dynamically updated based on membership functions (Table 3).

For example, for a 25-second cycle, the standard durations for the green, amber, and red traffic lights (at low traffic levels) are 7 s, 5 s, and 13 s, respectively. If the value of the membership function falls in the middle range, the duration of the green traffic signal increases by about 33% with a constant cycle time. In the high range, the increase in the duration of the green traffic signal can reach about 66%.

A similar mechanism for adjusting the duration of green, amber, and red traffic lights is implemented for a 40-second cycle. It allows dynamically adjusting the traffic light phases to optimize the traffic flow and improve pedestrian safety in different conditions.

Since the input data in the mechanism of logical conclusion are fuzzy variables, the fuzzy logic controller must convert these fuzzy outputs into clear values through defuzzification. It allows the actual system to process the result (Table 4).

As shown in Table 4, the output values of the fuzzy logic controller are determined based on six fuzzy rules using the "IF-THEN" construct. For example, if there is a peak period and the number of pedestrians is low, the

Table 3 *Variation of traffic light modes of the fuzzy logic controller*

Membership function	Duration of green signal, sec	Duration of amber signal, sec	Duration of red signal, sec
Traffic light cycle duration - 25 sec			
Low level	7	5	13
Medium level	9 (increase of the phase by 33%)	5	11
High level	12 (increase of the phase by 66%)	5	8
Traffic light cycle duration - 40 sec			
Low level	13	5	22
Medium level	18 (increase of the phase by 33%)	5	17
High level	22 (increase of the phase by 66%)	5	13

Table 4 *Recommendations for selecting the rational traffic signal control modes*

Time of the day	Level of pedestrians	Duration of traffic light phase
Peak period	Low	Medium
Peak period	Medium	Medium
Peak period	High	High
Off-peak period	Low	Low
Off-peak period	Medium	Medium
Off-peak period	High	High

duration of the traffic light phase will be average. Since the results of logical conclusion are fuzzy variables, a fuzzy logic controller converts these fuzzy outputs into clear values using the defuzzification method for the actual system to use them.

For example, in the case of a traffic light cycle (25 or 40 sec), if the result of defuzzification (i.e., a numerical value, not a linguistic value) falls in the middle range, the values for the green, amber, and red light times will be as follows: for a 25-sec cycle: the green phase lasts 9 sec, the amber phase - 5 sec, and the red phase - 11 sec; for a 40-sec cycle: the green phase lasts 18 sec, the amber phase - 5 sec, and the red phase - 17 sec.

These values adjust the duration of the traffic light phase according to the existing traffic conditions.

Thus, defuzzification ensures that the controller's fuzzy results are converted into specific, clear values that can be used to control the traffic signal, ensuring that the duration of the traffic signal phases is optimized to match the existing traffic conditions at the intersection.

5 Discussion

Creating a simulation model to study the rational mode of control at pedestrian crosswalks is critical in determining the optimal conditions for pedestrian and vehicle traffic at such crosswalks. The aim of this process is to ensure the maximum safety and efficiency in managing pedestrian flows.

Based on the results of studies of traffic and pedestrian flows, as well as the parameters of the road network, the optimal control parameters were substantiated. The following main indicators determined the optimal mode of traffic signal control: the level of roadway congestion, the maximum length of the queue of vehicles approaching the stop-line, and the share of time when the restrictive signal is lit for the lane during the traffic signal control cycle. The applicability of these indicators was tested using the PTV VISSIM software. In addition, the pedestrian behavior was taken into account for three types of intersections, depending on the characteristics of traffic on them.

At the initial research stage, PTV VISSIM software was used to model the traffic flows. For this purpose, the initial conditions were set at which the traffic volume varied from 50 to 700 p.c.u./h. The lane capacity on the approach to the intersection was set at 800 p.c.u./h. This value corresponds to ideal traffic conditions, which are characterized by a homogeneous traffic flow (100% passenger cars), good driving conditions and high-quality road surface.

Traffic and pedestrian flows were simulated using various simulation methods, including the static setting of traffic light cycle times. The traffic light system was implemented with one group of signals, and its cycle time was 120 seconds, with alternating red and green signals. The share of the restrictive signal per lane in the traffic light cycle was determined by the ratio $\beta = t_r / T_r$ and varied from 10 to 105 sec. The regulatory limitation on the duration of the traffic light cycle ($25 < T_c < 120$) was also considered, and the value of the main phase duration for transport was not less than $t_p = 7$ sec. In addition, the installation of surveillance cameras was simulated through the external interface module provided by the PTV VISSIM program to implement the controller based on fuzzy logic. Even in this case, the fuzzy logic approach proposed in this article was applied to 25-120 sec cycles, which could dynamically change depending on the situation.

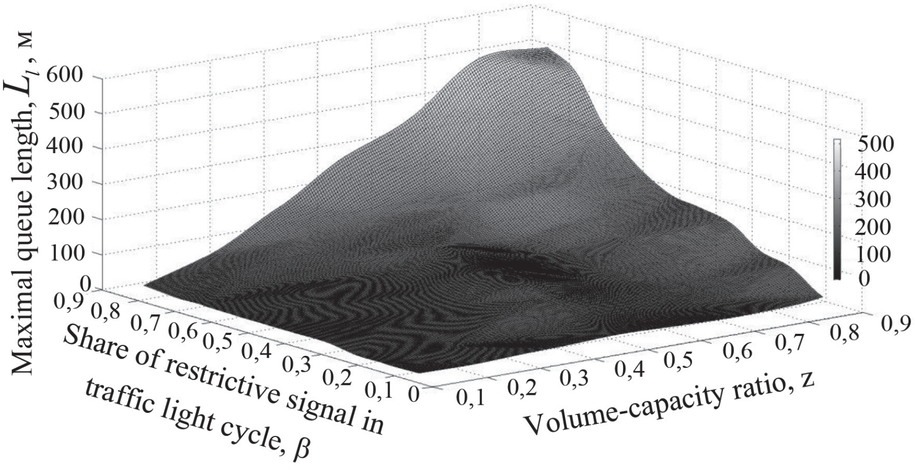
As for the pedestrian phases, the geometric parameters of the intersection did not change, and the duration of the transition interval was calculated taking into account the average speed of cars approaching the stop-line without braking. It made it possible to optimize the conditions for the safe passage of vehicles through the intersection and ensure the efficient use of traffic signals.

The results of the study, which reflect the change in the maximum queue length, depending on the volume-capacity ratio of the intersection before the stop-line and the share of the duration of the restrictive signal in the traffic lane in the control cycle for three types of intersections, are shown in Figure 5.

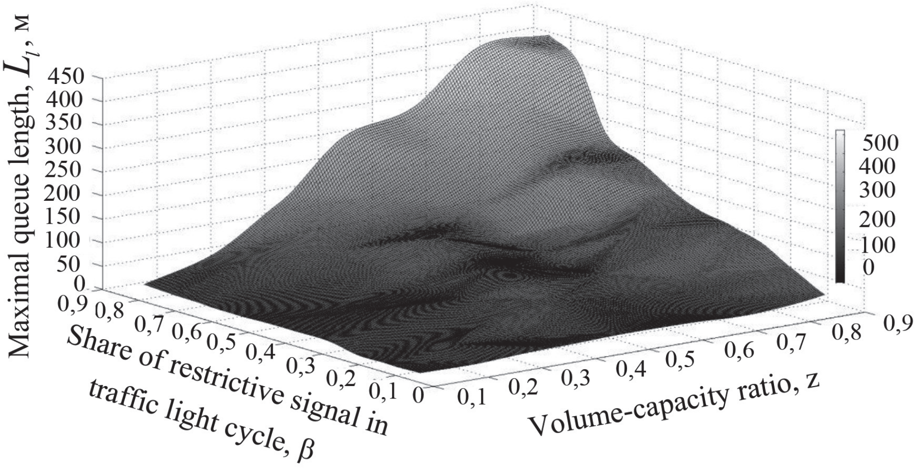
The graph in Figure 5 shows that increasing the duration of the pedestrian restrictive signal affects the share of pedestrians who cross the roadway at the restrictive signal, especially for the intersections of type I. It emphasizes the need to adjust the duration of the traffic signal cycle in areas with heavy pedestrian traffic. In addition, shortening the duration of the pedestrian signal reduces vehicle waiting time. If the traffic volume exceeds 500 veh/h per lane, this can lead to queues of vehicles longer than 90 m with a restrictive signal duration of 40 sec.

***Table 5** Dependencies of changes in the maximum queue length depending on the volume-capacity ratio and the share of the restrictive signal in the lane in the control cycle*

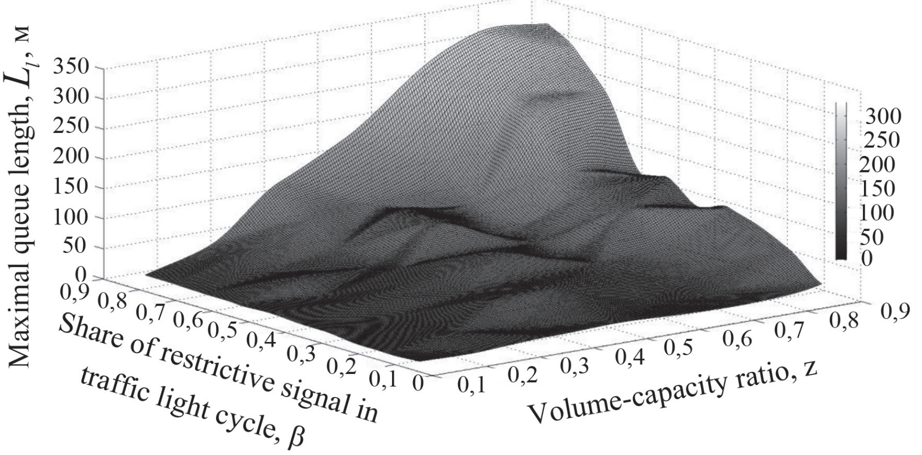
Type of intersection	Formulas	Coefficient of determination, R^2
I	$L_r = 156.42 - 265.018 \cdot z - 675.696 \cdot \beta + 117.453 \cdot z^2 + 915.616 \cdot z \cdot \beta + 563.626 \cdot \beta^2$	0.73
II	$L_r = 162.123 + 120.567 \cdot z + 45.432 \cdot \beta - 50.987 \cdot z^2 + 200.346 \cdot z \cdot \beta - 30.211 \cdot \beta^2$	0.72
III	$L_r = 112.852 + 115.568 \cdot z + 47.901 \cdot \beta - 55.436 \cdot z^2 + 198.765 \cdot z \cdot \beta - 28.346 \cdot \beta^2$	0.70



a)



b)



c)

Figure 5 *Change of the maximum queue length depending on the volume-capacity ratio of the roadway and the share of restrictive traffic signals: a - signalized crosswalk of type I; b - signalized crosswalks of type II; c - signalized crosswalks of type III*

After processing the modelling results, an empirical dependence was obtained of the maximum queue length on the volume-capacity ratio and the share of the restrictive signal in the traffic lane in the traffic light cycle (Table 5).

According to the modeling results, the maximum queue length of vehicles before the stop-line is the longest for intersections of type I located near transport hubs and reaches 504.6 m at a volume-capacity ratio of intersection 0.88 and share of a restrictive signal in the traffic lane 0.83. In comparison, for type II (in central areas) and type III (in residential areas) intersections, the queue length is reduced to 403.7 m and 317.9 m, respectively

These results indicate that at intersections of type I, where the traffic load is highest, the traffic signal control modes need to be optimized especially carefully to prevent the excessive vehicle delays. Reduced queue length at intersections of type II and III indicates that less stringent regulatory mechanisms can be applied in less congested areas.

The proposed approach allows reducing vehicle delays effectively and considers pedestrians' needs in traffic signal control systems. It can be especially useful in developing the optimal control strategies at intersections with high traffic volumes and significant pedestrian activity.

6 Conclusions

1. The analysis of patterns and methods for studying the behavior of road users revealed that optimization of traffic signal control modes and parameters depends on a number of factors, such as pedestrian and traffic volumes, waiting time, queue length, and the number of crossing violations. The main research methods used to set up the traffic signal control systems are observation, mathematical modeling, and statistical data analysis. These methods make it possible to adapt traffic light cycles to real traffic conditions to improve the safety and efficiency of traffic flows.
2. An experimental study was conducted at signalized intersections and a midblock signalized pedestrian crosswalk in Lviv. For signalized intersections with different traffic and pedestrian flow conditions, it was found that these conditions depend on the location in the city. Based on this, the intersections are divided into three types according to the traffic characteristics: type I - intersections near transport hubs where there is a high traffic volume and a significant number of pedestrians, especially near train stations, bus stations, and other main urban infrastructure facilities; type II - intersection in the central area of the city, where traffic flows are quite intense, and pedestrian traffic is generated mainly by commercial and business centers; type III - intersections in residential areas where the traffic volume is lower, but still many pedestrians cross roadways near schools, parks, and residential areas. It was found that in residential areas (type III), the share of pedestrian traffic violations is 9%, possibly due to fewer cars and a lower level of control. In the central areas of the city (type II), this indicator is somewhat lower - 7%, as traffic volume increases and people are less likely to ignore traffic signals in a fast-paced environment. Near transport hubs (type I), the share of violators reaches the highest level - 13%, possibly due to the large number of pedestrians and high level of haste.
3. The method of adaptive traffic control at pedestrian crossings has been improved. It considers not only the physical and psychophysiological capabilities of pedestrians but the factors that influence their behavior when deciding to cross the road, as well. The method includes elements of predicting pedestrian behavior based on previous observations and can be adapted to specific conditions of an intersection or crosswalk.
4. Based on the collected data and conducted research, recommendations were developed for choosing the optimal traffic signal control modes at different types of intersections. It takes into account traffic delays, pedestrian volume, and the level of traffic violations. It was found that:
   - ❑ for the two-phase control, the optimal cycle time should be between 25 and 70 sec, depending on the driving conditions;
   - ❑ for the three-phase control - from 40 to 90 sec, taking into account the needs of both vehicles and pedestrians;
   - ❑ for the four-phase control - from 60 to 120 sec, which provides the most comprehensive approach to control different flows.

These recommendations allow for flexible adjustment of traffic signal modes, which helps to reduce delays, increase safety at intersections and pedestrian crosswalks, and improve overall traffic efficiency in urban areas.

Acknowledgement

We would like to express our gratitude to Lviv municipal enterprise “Lvivavtodor” for its valuable assistance and cooperation during the experimental study. Your support and professionalism were an important contribution to the results of our work.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] BOIKIV, M., POSTRANSKYY, T., AFONIN, M. Establishing patterns of change in the efficiency of regulated intersection operation considering the permitted movement directions. *Eastern-European Journal of Enterprise Technologies* [online]. 2022, **118**(3), p. 17-26. ISSN 1729-3774. Available from: https://doi.org/ 10.15587/1729-4061.2022.262250

[2] FORNALCHYK, Y., KODA, E., KERNYTSKYY, I., HRYTSUN, O., ROYKO, Y., BURA, R., OSINSKI, P., BARABASH, R., HUMENUYK, R., POLYANSKY, P. The impact of vehicle traffic volume on pedestrian behavior at unsignalized crosswalks. *Roads and Bridges - Drogi i Mosty* [online]. 2023, **22**(2), p. 201-219. eISSN 2449-769X. Available from: https://doi.org/10.7409/rabdim.023.010

[3] HASSAN, S., HOUNSELL, N., SHRESTHA, B. Investigating the applicability of upstream detection strategy at pedestrian signalised crossings. *Promet - Traffic and Transportation* [online]. 2017, **29**(5), p. 503-510. ISSN 1848-4069. Available from: https://doi.org/10.7307/ptt.v29i5.2225

[4] PAU, G., CAMPISI, T., CANALE, A., SEVERINO, A., COLLOTTA, M., TESORIERE, G. Smart pedestrian crossing management at traffic light junctions through a fuzzy-based approach. *Future Internet* [online]. 2018, **10**(2), 15. ISSN 1999-5903. Available from: https://doi.org/10.3390/fi10020015

[5] HO, T., CHUNG, M. Information-aided smart schemes for vehicle flow detection enhancements of traffic microwave radar detectors. *Applied Sciences* [online]. 2016, **6**(7), 196. eISSN 2076-3417. Available from: https://doi.org/10.3390/app6070196

[6] EL HAMDANI, S., BENAMAR, N., YOUNIS, M. Pedestrian support in intelligent transportation systems: challenges, solutions and open issues. *Transportation Research Part C: Emerging Technologies* [online]. 2020, **121**, 102856. ISSN 0968-090X. Available from: https://doi.org/10.1016/j.trc.2020.10285

[7] SALVO, G., CARUSO, L., SCORDO, A., GUIDO, G., VITALE, A. Traffic data acquirement by unmanned aerial vehicle. *European Journal of Remote Sensing* [online]. 2017, **50**(1), p. 343-351. eISSN 2279-7254. Available from: https://doi.org/10.1080/22797254.2017.1328978

[8] BRANQUINHO, J., SENNA, C., ZUQUETE, A. An efficient and secure alert system for vanets to improve crosswalks' security in smart cities. *Sensors* [online]. 2020, **20**(9), 2473. eISSN 1424-8220. Available from: https://doi.org/10.3390/s20092473

[9] ZHANG, H., ZHANG, C., WEI, Y., CHEN, F. Effects of mobile phone use on pedestrian crossing behavior and safety at unsignalized intersections. *Canadian Journal of Civil Engineering* [online]. 2019, **46**(5), p. 381-38. ISSN 0315-1468, eISSN 1208-6029. Available from: https://doi.org/10.1139/cjce-2017-0649

[10] GIUFFRE, T., CAMPISI, T., TESORIERE, G. Implications of adaptive traffic light operations on pedestrian safety. *IOSR Journal of Mechanical and Civil Engineering* [online]. 2017, **13**, p. 58-63. eISSN 2278-1684. Available from: https://doi.org/10.9790/1684-1306045863

[11] BARBERI, S., ARENA, F., TERMINE, F., CANALE, A., OLAYODE, I. Safety aspects of intelligent transport systems applied to road intersections. *AIP Conference Proceedings* [online]. 2022, **2611**(1), 060012. ISSN 1551-7616. Available from: https://doi.org/10.1063/5.0119774

[12] CHOI, J., AHN, B., KWEON, I. Crosswalk and traffic light detection via integral framework. In: The 19th Korea-Japan Joint Workshop on Frontiers of Computer Vision: proceedings [online]. IEEE. 2013. ISBN 978-1-4673-5620-6, eISBN 978-1-4673-5621-3, p. 309-312. Available from: https://doi.org/10.1109/FCV.2013.6485511

[13] MURALIDHARAN A., COOGAN, S., FLORES, C., VARAIYA, P. Management of intersections with multi-modal high-resolution data. *Transportation Research Part C: Emerging Technologies* [online]. 2016, **68**, p. 101-112. ISSN 0968-090X. Available from: https://doi.org/10.1016/j.trc.2016.02.017

[14] GUANETTI, J., KIM, Y., BORRELLI, F. Control of connected and automated vehicles: state of the art and future challenges. *Annual Reviews in Control* [online]. 2018, **45**, p. 18-40. ISSN 1367-5788. Available from: https://doi.org/10.1016/j.arcontrol.2018.04.011

[15] ROYKO, Y., HRYTSUN, O., BURA, R., YEVCHUK, Y. Provision of a rational control mode at pedestrian crosswalk. *MATEC Web of Conferences* [online]. 2024, **390**, 03011. eISSN 2261-236X. Available from: https://doi.org/10.1051/matecconf/202439003011

[16] ALVER, Y., ONELCIN, P. Gap acceptance of pedestrians at overpass locations. *Transportation Research Part F: Traffic Psychology and Behaviour* [online]. 2018, **56**, p. 436-443. ISSN 1369-8478. Available from: https://doi.org/10.1016/j.trf.2018.05.010

[17] HASSAN, S., HOUNSELL, N., SHRESTHA, B. Verification of puffin modelling using VISSIM. *Journal Technology / Jurnal Teknologi* [online]. 2013, **65**(3), p. 81-84. ISSN 2180-3722. Available from: https://doi.org/10.11113/jt.v65.2150

[18] FAYYAZ, K., SCHULTZ, G., GALVEZ DE LEON, P. Driver compliance at enhanced pedestrian crossings in Utah (No. UT-19.03). Utah: Department of Transportation, 2019.

[19] KHATTAK, Z., MAGALOTTI, J., FONTAINE, M. Estimating safety effects of adaptive signal control technology using the Empirical Bayes method. *Journal of Safety Research* [online]. 2018, **64**, p. 121-128. ISSN 0022-4375. Available from: https://doi.org/ 10.1016/j.jsr.2017.12.016

[20] ASAITHAMBI, G., KUTTAN, M., CHANDRA, S. Pedestrian road crossing behavior under mixed traffic conditions: a comparative study of an intersection before and after implementing control measures. *Transportation in Developing Economies* [online]. 2016, **2**(2), 14. eISSN 2199-9295. Available from: https://doi.org/ 10.1007/s40890-016-0018-5

[21] ASLANI, M., SEIPEL, S., MESGARI, M., WIERING, M. Traffic signal optimization through discrete and continuous reinforcement learning with robustness analysis in downtown Tehran. *Advanced Engineering Informatics* [online]. 2018, **38**, p. 639-655. ISSN 1474-0346. Available from: https://doi.org/10.1016/j.aei.2018.08.002

[22] FRICKER, J., ZHANG, Y. Modeling pedestrian and motorist interaction at semi-controlled crosswalks: The effects of a change from one-way to two-way street operation. *Transportation Research Record* [online]. 2019, **2673**(11), p. 433-446. ISSN 0361-1981. Available from: https://doi.org/10.1177/0361198119850142

[23] HRYTSUN, O. Impact of traffic volume and composition on the change in the speed of traffic flow. *Transport Technologies* [online]. 2023, **2023**(1), p. 12-20. eISSN 2709-5223. Available from: https://doi.org/10.23939/tt2023.01.012

[24] ADAM, I., WAHAB, A., YAAKOP, M., SALAM, A., ZAHARUDIN, Z. Adaptive fuzzy logic traffic light management system. In: 2014 4th International Conference on Engineering Technology and Technopreneuship ICE2T: proceedings [online]. 2014. ISBN 978-1-4799-4621-1, p. 340-343. Available from: https://doi.org/ 10.1109/ICE2T.2014.7006274

[25] BI, Y., SRINIVASAN, D., LU, X., SUN, Z., ZENG, W. Type-2 fuzzy multi-intersection traffic signal control with differential evolution optimization. *Expert Systems with Applications* [online]. 2014, **41**, p. 7338-7349. ISSN 0957-4174. Available from: https://doi.org/10.1016/j.eswa.2014.06.022

[26] STOTSKO, Z., FORNALCHYK, Y., MOHYLA, I. Simulation of signalized intersection functioning with fuzzy control algorithm. *Transport Problems*. 2013, **8**(1), p. 5-16. eISSN 2300-861X.

[27] MONTGOMERY, D., RUNGER, G. *Applied statistics and probability for engineers*. John wiley and sons, 2020. ISBN 978-1119746355.