Provision of a rational control mode at pedestrian crosswalk

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Abstract. Signalized pedestrian crosswalks on urban streets are essential for ensuring the safe crossing of the roadway by pedestrians and controlling the movement of vehicles. These crosswalks allow pedestrians to cross the roadway by the set rules, providing safety and comfort to all road users. Pedestrian safety is critical to improving mobility in cities. About 15% of traffic accidents occur at signalized crosswalks. Existing traffic signal control systems are mainly aimed at road traffic, which often results in significant delays and insufficient time for pedestrians to cross. It leads to risky behavior, such as not obeying traffic rules. Current pedestrian detection systems at signalized intersections mainly consist of pedestrian controllers called "buttons". Limitations include the inability to notify a pedestrian that he, or she has been detected and the inability to dynamically extend crossing times if pedestrians do not cross the road in time. Intelligent transport systems play an essential role in improving mobility and safety and provide innovative methods to connect pedestrians, vehicles and infrastructure. Most of the research on smart and connected technologies focuses on vehicles, but there is a need to use these technologies to study pedestrian behavior, as pedestrians are the most vulnerable participants in the transportation system. Therefore, the transport system should take into account all pedestrians and satisfy all needs. Therefore, this article aims to provide information on improving traffic signal control system at pedestrian crosswalks to make them more pedestrian-friendly without significant disruption to traffic flow. The study was carried out by modeling a pedestrian crosswalk for different combinations of pedestrians and traffic flow. This paper presents modeling results and provides recommendations for the introduction of a rational control mode at pedestrian crosswalks.

1 Introduction

Pedestrian crosswalks are an integral part of the street and road network and play an important role in ensuring the safety of pedestrians. It is necessary to take into account two key aspects – pedestrian safety and traffic efficiency to guarantee a rational mode of control at pedestrian crosswalks [1].

First and foremost, pedestrian safety should be the highest priority when controlling crosswalks. For this purpose, it is important to use various measures to minimize the risk of road accidents and create comfortable conditions for pedestrians to cross the roadway [2].

One of the most effective ways to ensure safety at pedestrian crosswalks is to install traffic lights. They regulate traffic and pedestrian flows, indicating a time when pedestrians can cross the roadway. The precise location of traffic lights and proper setting of their control time plays a decisive role in pedestrian safety. Provision of sufficient time for crossing, especially for people with limited mobility or pedestrians in high density, is necessary condition for a rational control mode [3].

Traffic light control is usually aimed at minimizing the delay of traffic flow while ensuring a minimum time for pedestrians to cross [1,3]. Road transport is usually the main target for improving the performance of the transport system. In the system of traffic light control, pedestrians often receive much less attention than other types of transport, in particular motor vehicles [2-4]. Pedestrians are often given the right to cross a roadway only after the detectors have determined that there is no delay to traffic flow, even if this results in a longer wait for pedestrians. It leads to the risky behavior of pedestrians when they start to cross the road despite the red signal at the traffic light. It often results in inequities in conditions where the delay of pedestrians significantly exceeds the delay of traffic flow. This disparity drives the need to rethink traffic control at such crosswalks to provide more benefits to both pedestrians and vehicles.

2 Analysis of literary sources andproblem statement

Management of traffic and pedestrian flows is mainly based on the principle of strict regulation or on the condition that pedestrians press a button to receive a permission signal. The problem is that not all pedestrians who want to cross the road press the signal call button. There are several possible reasons why pedestrians do not use this button [3,5]. For example, pedestrians may

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not know to press the button because some traffic lights do not have a visible button. Even if pedestrians are aware of this requirement, the delay between the moment the button is pressed and the "crossing allowed" signal can be long, leading pedestrians to think the system is not working. Pedestrians with vision problems may not be aware of this button or may not be able to find it. In any case, as a result, pedestrians may try to cross the road without waiting for a traffic light signal.

Various automatic pedestrian detection technologies have been proposed to improve the efficiency of traffic signal management and avoid the need to press the button to call the traffic signal. Such technologies include the use of detectors to detect pedestrians on sidewalks and controlled crosswalks [1, 5-8].

Pedestrian detection is the basis of the pedestrian control strategy at controlled crosswalks. When the detector is fully functional, it allows such crosswalks to provide real advantages comparing with signalized pedestrian crosswalks with fixed-time control. These advantages are aimed at two main areas [2, 9]:

– optimize the time pedestrians cross the roadway. For signalized crosswalks, the duration of the pedestrian crossing is fixed, and it usually lasts long enough so that, even with heavy pedestrian flow volume, pedestrians have enough time to cross before cars are allowed to move.

– minimization of unnecessary car stops. Pedestrians don't always wait for the traffic light to turn green to cross the roadway. In some cases, pedestrians may also change their minds and decide not to cross, even if they have already pressed the call button. When using such crosswalks, the behavior of pedestrians leads to the transition to the "pedestrians have priority" mode, stopping the movement of all traffic, even if no one crosses the roadway [6].

This problem can be solved at signalized pedestrian crosswalks with the help of detectors on the sidewalk that respond to the presence of waiting pedestrians [4,8,10]. If all pedestrians move away from the crosswalk, the pedestrian right-of-way is cancelled, and more signal time is given to the traffic flow.

The use of detectors on sidewalks is challenging because the shape and size of the pedestrian detection zone on the sidewalk must be obtained.

Typically, simple detectors provide a roughly oval-shaped detection zone. While this is suitable for general vehicle detection, it is not well suited for the areas required for application on sidewalks. In these cases, it is necessary to detect pedestrians standing along the edge of the sidewalk (where an oval shape is acceptable) and when they are approaching or standing on the approach section of the sidewalk. In addition, it is critical to be able to detect pedestrians when they are standing close to the traffic light post, which usually has a built-in pedestrian detector.

Therefore, one of the key ways to solve problems with the performance of detectors is to direct two beams to the pedestrian waiting area [1,3,8,11]. One beam runs along the sidewalk edge, and the other runs perpendicular to the road, covering the approach area. It provides a zone shape suitable for application on the sidewalk.

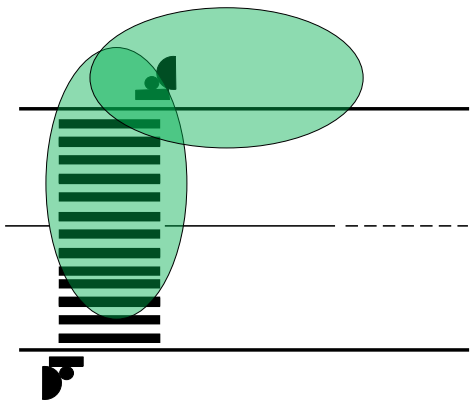

Fig. 1. Double detector area

According to this principle of operation, the detector takes pedestrians into account both for the crossing zone (detectors at the intersection) and the waiting zone on the sidewalk (detectors on the curb), as shown in Fig. 1.

Sensors located on the sidewalk allow for monitoring the presence of pedestrians and cancelling requests to cross the road if the pedestrian has already started crossing the roadway between cars [9-11]. It prevents unnecessary delays and ensures safety for pedestrians [3,12]. Special sensors are also used at the crosswalk to adjust the duration of the pedestrian crossing period automatically. It provides pedestrians enough time to cross safely, especially when there are many pedestrians at the crosswalk or when pedestrians are moving slowly [5,11,13]. Using such sensors helps optimize traffic light operation and provides more effective and safer pedestrian traffic control.

Also, a sufficient area where pedestrians can wait for the traffic light signal should be allocated on the sidewalk. This area should be sufficient to accommodate the expected number of pedestrians under normal conditions. The distance from the sidewalk to the curb should be less than 2 m for a crosswalk with a width of 2.4 m. In addition, sidewalks should have sufficient width for pedestrians who do not intend to cross the roadway [14].

For a more detailed study of the rational mode of control at the pedestrian crosswalk, it is necessary to conduct research by modeling the signalized pedestrian crosswalk using the PTV VISSIM software environment [15].

3 Research methodology

The experimental study was conducted at an isolated signalized pedestrian crosswalk located on Horodotska Str. in Lviv city. For this study, detectors of active movement of vehicles and pedestrians were used.

The purpose was to check the effectiveness and adequacy of the proposed solutions for traffic management at pedestrian crosswalks. The controlled pedestrian crosswalk had only one lane in each direction without a central safety island. It created isolated conditions for the experiment, allowing for more accurate monitoring and analysis of pedestrian and vehicle traffic at the crosswalk.

During the study, various parameters were evaluated using data from a video recording at a signalized pedestrian crosswalk. The following indicators were obtained with the help of video recording: characteristics of vehicles and pedestrians; geometric parameters of the road network; the duration of the permissive signal for traffic and pedestrians; duration of the control cycle; pedestrian crossing time, etc. These results are necessary to create a simulation model in the PTV VISSIM software environment.

With the help of a video recording, the following input data were obtained for simulation modeling:
– single-lane roadway with a lane width of 3.5 m in both directions;
– traffic flow composition: 95% are cars, 3% – trucks and 2% – buses;
– the preferred speed distribution of the traffic flow for all types of vehicles varies from 23 km/h to 47 km/h;
– the preferred speed distribution for pedestrians varies from 4.3 km/h to 9.4 km/h;
– the behavior of pedestrians at signalized pedestrian crosswalk is as follows: 61% of pedestrians press the call button and follow the instructions of the traffic lights; 8.5% of pedestrians press the call button but cross the road when there is an opportunity; and 30.5% of pedestrians ignore traffic lights and cross the roadway when large intervals between vehicles are observed.

Recorded parameters of traffic lights, such as cycle duration and the minimum duration of the permitted signal of the traffic light for pedestrians, was provided by the "Lvivavtodor" LME. Some additional parameters were tested at the study site.

These data make it possible to create a simulation model of the vehicles movement and pedestrian behavior at a signalized crosswalk, which can be used to study different control modes.

Creating the simulation model to study a rational control mode at a pedestrian crosswalk is essential for determining the optimal conditions for the movement of pedestrians and vehicles at signalized crosswalks. Using the PTV VISSIM software environment, it is worth taking into account the safe and dangerous intervals that affect the movement of pedestrians to achieve this goal.

Safety intervals can be formed by long intervals between vehicle movements or drivers stopping to give way to pedestrians. Pedestrians, in turn, can make a decision – to cross the roadway or to wait, depending on whether an interval occurs that exceeds their critical interval.

In the PTV VISSIM software environment, using the critical interval parameter allows for the representation of this interaction between pedestrians and vehicles. If pedestrians see a gap that exceeds their critical interval, they will cross the roadway. Otherwise, they will wait for an acceptable interval that guarantees their safety.

A pedestrian's decision to cross a roadway can be described as a function of the pedestrian's critical delay time. Pedestrian delay is the time between the arrival of a pedestrian at the crosswalk and the arrival of the next conflicting vehicle at the crosswalk. In the simulation model, which uses the PTV VISSIM software environment, pedestrians consider a time interval of at least 6 seconds for single-lane traffic in opposite directions of vehicles. If the delay time of the pedestrian before the next vehicle's arrival is greater than or equal to this critical interval, the pedestrians decide to cross the road.

This model allows taking into account the delay time of the pedestrian, as well as controlling their decision to cross the road, which contributes to ensuring the safety and efficiency of pedestrian movement at signalized crosswalks.

It is necessary to carry out simulation modeling in the PTV VISSIM software environment to provide a rational control mode for the pedestrian crosswalk. In the simulation model, any vehicle detected within 4 s of the one in front will extend the permissive signal of the traffic light for 4 s. While determining the rational control mode, the presence of pedestrians is also recorded using the detector. The information is transmitted to the signal controller when pedestrian detection is activated before the crosswalk. After recording the pedestrians, two traffic conditions are checked before changing the traffic signal to a pedestrian:
– minimum permissive traffic light signal duration for traffic flow;
– the maximum permissive traffic light signal duration for the traffic flow, provided that small intervals between vehicles are recorded (less than 4 s).

If the first condition is fulfilled (minimum permissive signal duration for the traffic flow), then the next condition is the absence of intervals between vehicles or reaching the maximum permissive signal duration for the traffic flow.

If any of these conditions are met (i.e. there is an inter-vehicle gap of more than 4 s or the maximum permissive duration of traffic lights for the traffic flow is reached), then the pedestrian phase starts. It is assumed that if all these conditions are met after the activation of pedestrian detection before the crosswalk, then the permissive signal for pedestrian flow will start after 4 seconds.

An approach based on analyzing the delays of vehicles and pedestrians is used to evaluate the effectiveness of the control mode management at the pedestrian crosswalk. Simulation modeling using the PTV VISSIM software product is used for evaluation in this study. Previous studies have confirmed that PTV VISSIM is a powerful and effective tool for modeling different types of pedestrian behavior and their interaction with traffic flows. Considering these properties, it is possible to adequately reproduce real-time traffic dynamics and interaction between pedestrian and traffic flows.

This methodology allows for analyzing different control options for the control mode at a pedestrian crosswalk and determining their effects on delays for both pedestrians and vehicles. It is essential information for making decisions about the optimal control mode that would ensure the safety and efficiency of movement at pedestrian crosswalks.

4 Research results

The location of pedestrian detectors before a crosswalk plays an essential role in the effectiveness of traffic control at the crosswalk. Optimum placement of detectors can significantly improve the operation of the control system and reduce delays for pedestrians and vehicles.

If the detectors are too close to the sidewalk, it can cause excessive signal activation due to unnecessary detection of pedestrians who are not yet ready to cross the roadway. As a result, unnecessary delays are created for vehicles, and the waiting time for all road users increases. On the other hand, if the detectors are located too far from the sidewalk, this may result in the system not being able to detect pedestrians approaching the crosswalk in time. It can lead to underutilization of pedestrian clearance intervals, again causing delays for all road users and increasing the risk to pedestrian safety.

Therefore, the optimal location of pedestrian detectors is to find a balance between the accuracy of pedestrian detection and the efficiency of traffic control. It is an important aspect of ensuring safety and optimizing traffic at pedestrian crosswalks.

Theoretically, the detector located before the pedestrian crosswalk should be at a distance equal to the inter-interval time. It ensures the activation of a green signal for pedestrians when a pedestrian who is within the range of the detector crosses the roadway.

However, the optimal detection distance may be different when considering delays for both pedestrians and traffic flow. Therefore, simulation modeling was carried out at four different distances of pedestrian detection before the crosswalk: immediately before the crosswalk, in the zone of 3 m, 5 m, and 10 m.

It was found that the speed of pedestrians varies from 4.3 to 9.4 km/h, and the detection distance of pedestrians in front of a crosswalk is 3 m. The results show that the range of pedestrian arrival time at the crosswalk is from 1.2 to 2.5 s. A detailed analysis showed that 85% of pedestrians arrive at the crosswalk in an interval of 1.2 to 2 s, while the other 15% fall in the range from 2 to 2.5 s. Taking into account the speed of pedestrian movement, which corresponds to 1.3 m/s (this value is used in the design of pedestrian crosswalks), and the inter-interval time of 4 s, it was determined that the optimal distance for detecting pedestrians before the pedestrian crosswalk should be 5.2 m. In this regard, 5 m distance was used in this study. The choice of a distance of 10 meters was made arbitrarily, as a double distance of 5 m.

The input data for simulation modeling were the following results of field studies: traffic flow volume – 600 units/h; pedestrian flow volume is 200 ped/hour (for both directions). Later, a study was conducted with different pedestrian detection distances to determine the effect of different traffic combinations on the efficiency of the rational control mode.

Fig. 2 shows the results of the simulation modeling of the determination of traffic and pedestrian delays for different variants of pedestrian detection (immediately before the crosswalk, 3 m, 5 m, and 10 m).

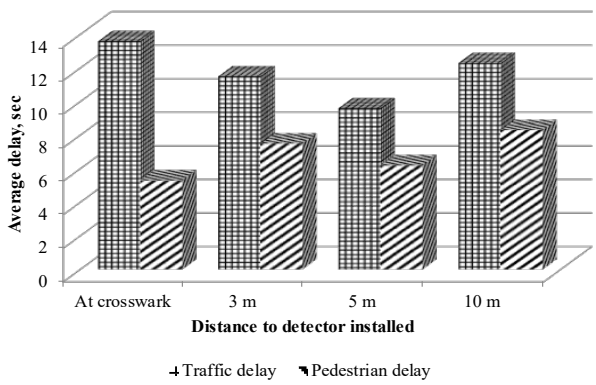

Fig. 2. The influence of the detector installation distance on the delays of traffic and pedestrian flows

Having analyzed Fig. 2., we can see that increasing the detection distance of pedestrians before the crosswalk leads to increased delays for vehicles and simultaneously decreases the delay for pedestrians in all considered options. This result is predictable since detecting pedestrians before a crosswalk leads to a more frequent provision of pedestrian phases. It, in turn, leads to more frequent traffic stops, resulting in increased vehicles delays. Having analyzed delays for both types of traffic, we have found that the smallest delay for traffic and pedestrians is observed at a pedestrian detection distance of 5 m. It was the distance used in the subsequent stages of simulation modeling.

The effective usage of detectors to detect pedestrians before crosswalks depends on the different volumes of traffic and pedestrian flow. For example, with a high volume of pedestrian flow and low traffic signals, traffic lights can work mainly for the minimum time allowed for traffic. In this case, the duration of traffic signals and traffic or pedestrian delays will not change due to the further increase in pedestrian flow volume. Therefore, the impact of detecting pedestrians before the crosswalk was investigated for different traffic and pedestrian flows volumes (Table 1). Traffic and pedestrian flows are taken into account for both directions of traffic.

Table 1. Incoming volumes of traffic and pedestrian flow

Traffic flow volume, p.c.u./h	Pedestrian flow volume, ped/h
100	100
	300
	500
300	100
	300
	500
500	100
	300
	500
700	100
	300
	500
900	100
	300
	500

These options for traffic and pedestrian flows volumes were simulated with and without pedestrian

detectors. In the case of detecting pedestrians before the crosswalk, the detector on the approach was placed at a distance of 5 m from the sidewalk. Fig. 3 shows the change in the number of traffic light cycles during an hour with and without using detectors at different volumes of traffic and pedestrian flows.

Having analyzed Fig. 3, we can see that the number of cycles increases in case when there is a pedestrian detector before the crosswalk compared to its absence. Detecting pedestrians before crosswalks with the help of a detector provides an additional opportunity to enter the pedestrian phase earlier, resulting in a reduced pedestrian delay. In this case, the duration of the permissive signal of the traffic light for the traffic flow is reduced if pedestrians are detected before the crosswalk (Fig. 4).

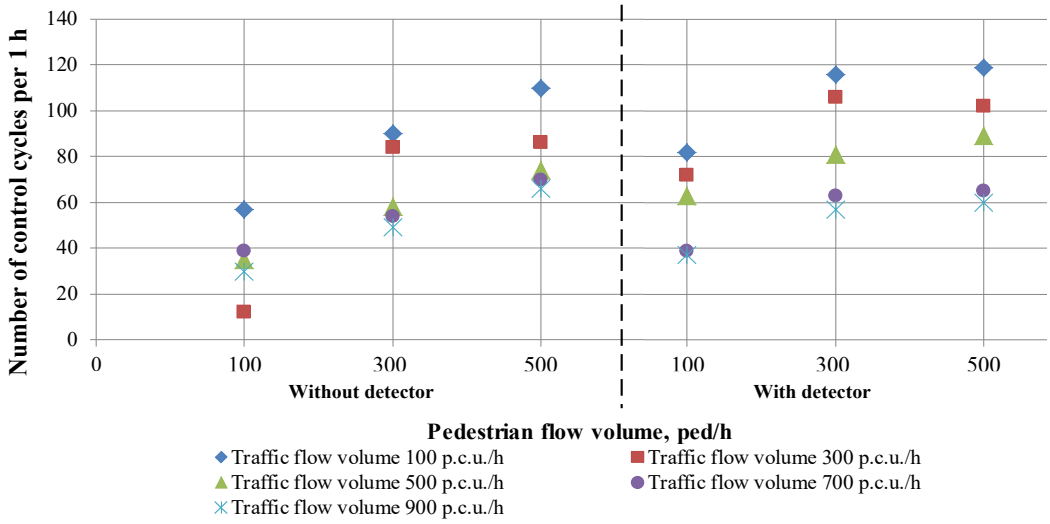

Fig. 3. Change in the number of traffic light cycles during the hour with and without the use of detectors at different volumes of traffic and pedestrian flows

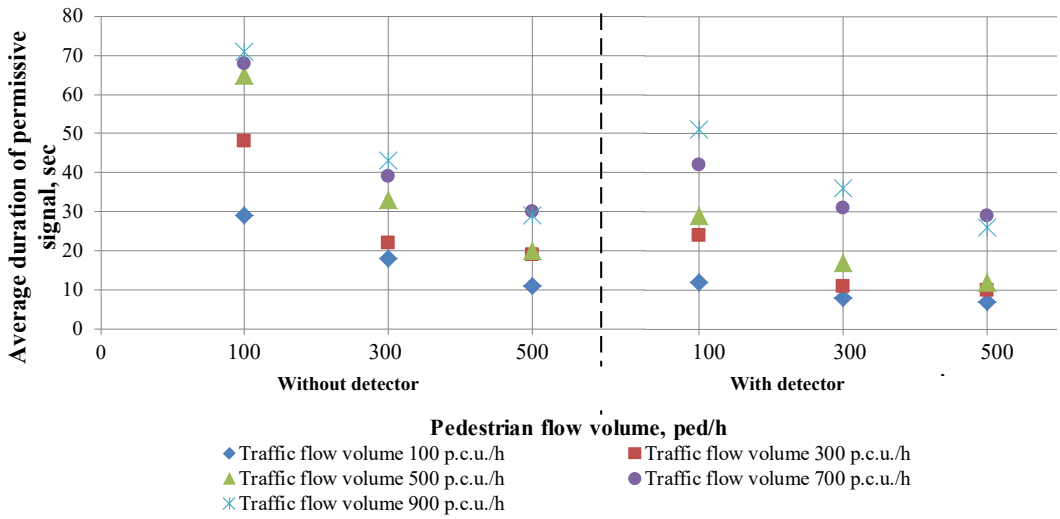

Fig. 4. Change in the average duration of the traffic light's permissive signal under different control modes

Fig. 4 shows that with high volumes of traffic and pedestrian flow (900 p.c.u./h and 500 ped/h), the average duration of the traffic light signal changes (less than 30 s) for the control mode without taking into account the detector, which considers the detection of pedestrians, and 26 s taking into account pedestrian detector. However, at lower traffic flow (100 p.c.u./h) and pedestrian flow (300 ped/h), use of pedestrian detectors before the crosswalk results in a reduction in the average signal clearance time (by approximately half in many options). It is explained by the fact that at a low volume of the traffic flow (approximately 100 p.c.u./h and 300 ped/h), the requirement to change the control phase is met more easily.

Fig. 5 shows the results of the simulation modeling of determining the delay of vehicles in the case of the presence of a detector for detecting pedestrians and in its absence. Simulation modeling results were carried out for all possible options.

Having analyzed Fig. 5, we can say that in all variants, a longer delay of vehicles is observed in the case of installing a pedestrian detector compared to not installing it. It is due to frequent calls from pedestrians, resulting in more frequent changes of control phases and reduced signal clearance time for vehicles. In addition, in

Fig. 5, it can be seen that the delay of vehicles increases as the volume of pedestrian and/or traffic flow increases. The change in vehicle delay when a pedestrian detector was installed before the crosswalk was relatively smaller for high pedestrian flow (500 ped/h) comparing to low pedestrian flow. The results of determining pedestrians delay for all variants of simulation modeling are shown in Fig. 6.

Fig. 6 shows that using a detector to detect pedestrians before crosswalks causes a reduction in pedestrian delay in all options. The level of reduction is much greater at a low volume of pedestrian flow (100 ped/hour) than at a high volume (500 ped/hour).

Based on simulation modeling results, a summary of possible options for using pedestrian detectors before the crosswalk is given (Table 2).

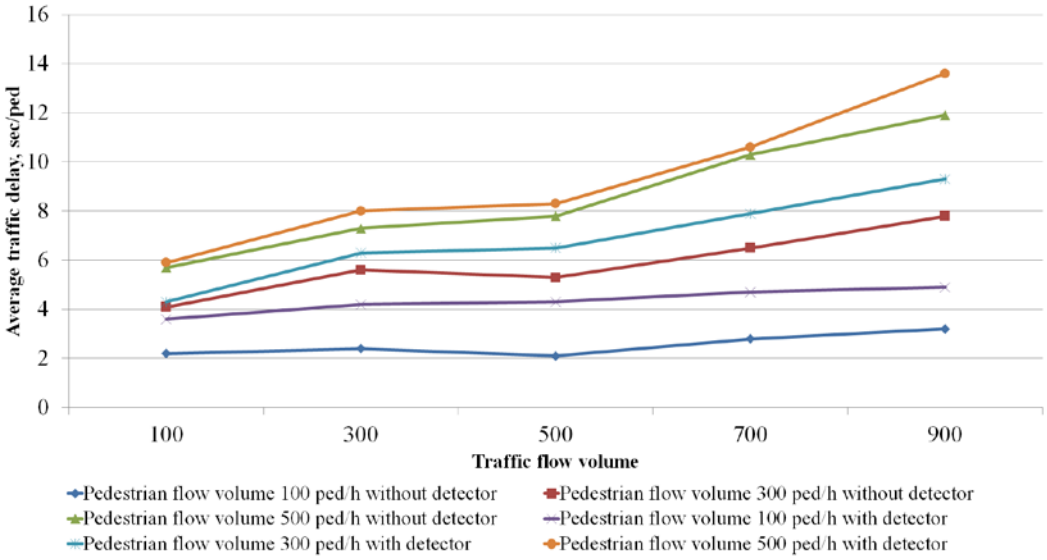

Fig. 5. Change in the average delay of vehicles depending on the change in the pedestrian flow volume

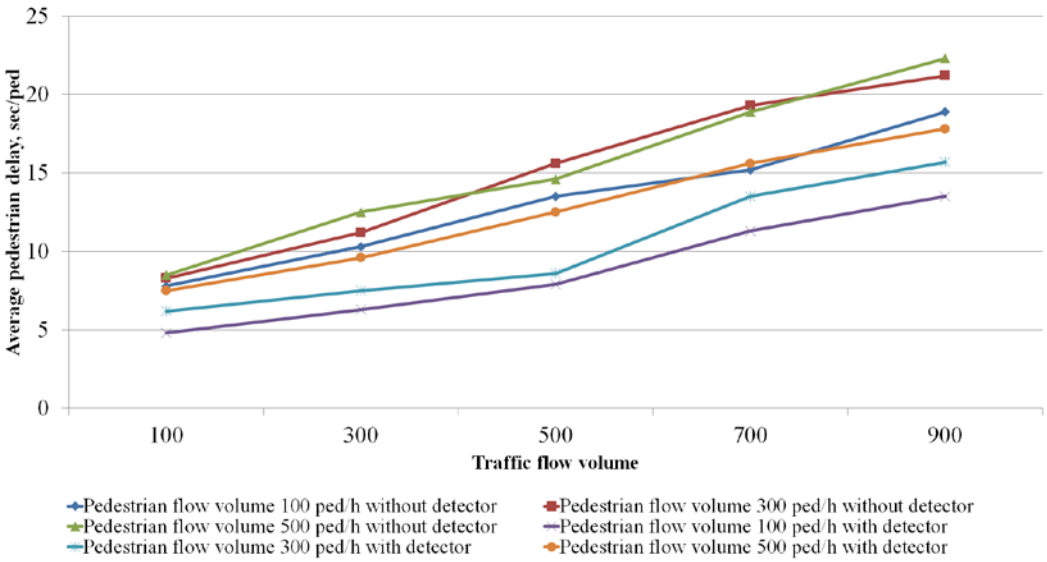

Fig. 6. Change in the average pedestrian delay depending on the change in pedestrian flow volume

Table 2. Recommendations for the use of pedestrian detectors before crosswalk depending on the volumes of traffic and pedestrian flow

Traffic flow volume, auto/h	Pedestrian flow volume, ped/h		
	100	300	500
100	√√	√√	√√
300	√	√	√
500	√x	√x	x
700	xx	x	x
900	xx	xx	x

Note: √√ – it is recommended to use a detector; √ – it is possible to use a detector; √x – it is probably possible to use a detector; xx – it is possible to use a detector; x – it is ineffective to use the detector.

Table 2 shows that implementing pedestrian detectors before pedestrian crosswalks has a clear advantage at low traffic flow volume (100 p.c.u./h). A small positive effect on reducing traffic delay was observed at a traffic flow volume of 300 p.c.u./h at all different pedestrian flow volumes. However, with a high traffic flow volume, there is an increase in the overall traffic delay.

5. Discussion and conclusion

Conducting a simulation with different options for the location of pedestrian detectors before crosswalks and different traffic flow volumes allowed us to show that the best location of the detectors among those that were tested was 5 m before the crosswalk. According to this option, the control mode is rational in places with low traffic flow volume. The pedestrian detector before the crosswalk is set, assuming all pedestrians cross the roadway at the specified location. However, in reality, some pedestrians may move to the side and cross when they find a suitable gap in the traffic flow, resulting in reduced traffic delays.

The results presented in the paper depend on assumptions about the behavior of pedestrians in a crosswalk – especially with large flow intervals. If there is a high percentage of pedestrians crossing the roadway using gaps in the flow at a specified site, the benefit of installing a pedestrian detector will be less than that stated in this article.

In general, using signalized pedestrian crosswalks involves providing safe interaction between pedestrians and traffic flows since totally separating these two categories of road users is impossible. A reduction in pedestrian delay can lead to an increase in vehicular delay. However, using pedestrian detection at signalized crosswalks can reduce pedestrian delay without significantly increasing vehicle delay. It is achieved by being able to detect pedestrians earlier and turn on the permissive signal of the traffic light for them. Implementing such measures is expected to improve the safety of pedestrians on congested roads and improve the operation of signalized crosswalks, allowing less disruption to the movement of both vehicles and pedestrians.

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