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IMPACT OF PEDESTRIAN FLOWS ON TRAFFIC DELAYS BEFORE ROUNDABOUTS

Summary. *The paper examines a roundabout located in a residential district of Lviv city. The area has many attraction points, so traffic and pedestrian flow volumes are large. All approaches to the roundabout have unsignalized pedestrian crosswalks, three of which lack safety islands. Field studies were conducted on peak and off-peak periods, collecting primary indicators of traffic and pedestrian flows. Traffic flow delays were determined on the approaches to the roundabout under existing traffic conditions with the help of the PTV VISSIM software. Three options were proposed for arranging pedestrian crosswalks on approaches to the roundabout. The first option was an arrangement of safety islands on all pedestrian crosswalks. The second option was an arrangement of underground pedestrian crosswalks. The third option was the implementation of adapting traffic light control with a call button for pedestrians. Traffic simulation was carried out for all three proposed options with the finding of the delay per vehicle and the values of the average and maximum length of the queue of vehicles on the approaches to the roundabout. All three options showed better results of traffic delay than existing conditions. However, there were delays caused by the traffic flow itself. These delays are seen in the results of the simulation of option two. Traffic delays are the smallest at this option. Option one showed the highest values of traffic delays in comparison with the other two options. The advantages and disadvantages of each option for arranging pedestrian crosswalks are determined. Recommendations are given regarding the feasibility of locating various types of pedestrian crosswalks on the approaches to the roundabout. Given the research results, the best option from the view of traffic and pedestrian flows, their delays and safety is the third one.*

Keywords: *traffic flow, pedestrian flow, roundabout, road safety, traffic simulation, unsignalized pedestrian crosswalk.*

1. INTRODUCTION

Not enough attention is paid to road users who use alternative means of movement, namely walking, cycling, or electric scooters, to solve the problems caused by the increasing the number of cars in cities. Along with transport infrastructure, pedestrian and bicycle infrastructure in Ukraine is underdeveloped. Very often, there is an unsatisfactory condition of pedestrian paths, lack of bicycle paths, insufficient number of pedestrian crosswalks, or presence of underground or aboveground pedestrian crosswalks with missing ramps or elevators for people with reduced mobility.

At the same time, there is the issue of pedestrian accessibility to points of attraction, especially in residential areas. Cases are often observed when residential areas cross arterial streets of district or citywide significance. At the same time, schools, kindergartens, shopping centers, etc., are located on both sides of the street. At the same time, pedestrian crosswalks are either located in inappropriate places for pedestrians or are absent. Another problem is unsignalized pedestrian crosswalks on such streets. First, they create a danger to vehicles riding at higher speeds and having to slow down when pedestrians start to cross the roadway, and to pedestrians who may misjudge the intervals and start crossing the roadway when cars are close enough to create a dangerous situation. Pedestrians also tend to violate traffic rules, abusing their right of way when crossing unsignalized pedestrian crosswalks, not making sure the maneuver is safe, and suddenly entering the roadway. Secondly, high values of traffic and pedestrian volumes with uncontrolled crossing of the latter can cause significant delays for transport, especially during peak periods.

Roundabouts on arterial streets in residential areas require special attention. It is because at high values of traffic volumes and a significant share of left-turning flow the Sectoral Building Norms of Ukraine recommend designing large roundabouts (with a central island diameter of more than 60 m) [1]. Given the width of the roadway around this central island, the area of such intersections is very large and creates significant problems with pedestrian accessibility. Therefore, pedestrian crosswalks at such roundabouts are usually arranged as close as possible to the beginning of the circular flow to reduce the distances pedestrians should walk, that affects both traffic safety and traffic delays.

2. RESEARCH STATEMENT

Nowadays, in many large cities of Ukraine, including the city of Lviv, there are arterial streets in the residential areas with four or more lanes for traffic in one direction where significant volumes and speeds of traffic are presented. Residential areas mean unequivocally high volumes of pedestrian flows, especially during peak periods, when residents go to work, educational institutions, shopping centers, etc. Therefore, the problem of pedestrian accessibility in these areas should be solved first place. Namely, sufficient number of pedestrian crosswalks is needed while ensuring pedestrian safety and minimizing traffic delays. One more problem for pedestrians is the intersection of arterial streets, as their area is usually large, which creates additional inconvenience in getting to the destination. With lacking alternatives, pedestrians are forced to cross at such places. Given the high values of pedestrian volumes and frequent violations of traffic rules by pedestrians, it creates significant inconvenience for traffic flows approaching the intersections. In the Frankivskyi district of Lviv city, there are three roundabouts with large areas, and many attraction points near them. In addition, they are located in a residential area. Pedestrian crosswalks are installed at the approaches to all these intersections. Some of them have safety islands, but all of them are unsignalized. During peak periods, there is an almost continuous flow of pedestrians trying to cross the roadway, so vehicles first must stop before the pedestrian crosswalks to let pedestrians through, then again before the circular flow to let through vehicles moving around the central island and finally when exiting the circular flow, to also allow pedestrian flows cross the roadway.

State construction norms of Ukraine [2] determine that on streets with two or more traffic lanes in one direction, it is necessary to arrange safety islands at unsignalized pedestrian crosswalks or to implement traffic light signaling. As for the construction of aboveground or underground pedestrian crosswalks, they can be arranged only on arterial streets with continuous traffic, in compliance with all requirements for people with reduced mobility.

Therefore, the aim of our study is to analyze the impact of pedestrian flows on the delays of traffic flows on the approaches to the roundabout. We considered four options: unsignalized pedestrian crosswalk without safety islands (existing traffic conditions), unsignalized pedestrian crosswalk with existing safety islands, signalized pedestrian crosswalk, and underground pedestrian crosswalk.

It is necessary to complete the following tasks to achieve the aim:

- carry out field studies at the roundabout in peak and off-peak periods to determine the primary indicators of traffic and pedestrian flows and existing traffic conditions at the intersection;
- carry out traffic simulation with the determination of the delay of vehicles on the approaches to the roundabout under existing traffic conditions;
- carry out traffic simulation for three options for arranging pedestrian crosswalks before roundabouts;
- provide recommendations on the expediency of using various options for arranging pedestrian crosswalks before roundabouts.

3. THE ANALYSIS OF THE MAIN LITERARY SOURCES

The interaction of traffic and pedestrian flows has been studied for a long time. The increasing number of cars causes delays for traffic and pedestrians who want to cross the roadway at unsignalized pedestrian crosswalks. Conversely, the significant pedestrian volumes in places of concentration of attraction points can have a negative impact on traffic delays.

The authors [3] draw attention to the impact of pedestrians crossing the roadway in unauthorized places on traffic flow delays. It was found that smaller vehicles, due to their larger maneuverability, had slightly lower delay values than trucks. In general, the violation of traffic rules by pedestrians led to forming the conditions corresponding to the level of service E, which is close to traffic jam conditions. Therefore, the authors concluded that it is necessary to improve the pedestrian infrastructure and increase the number of pedestrian crosswalks in locations with high pedestrian volumes to prevent the formation of such situations.

The authors [4] studied traffic delays before unsignalized pedestrian crosswalks on different types of sections: in the area of the intersection and outside it. It was determined that the highest delays were observed at intersection in secondary directions. It is because here, the vehicles were affected not only by pedestrians crossing the roadway, but also by vehicles moving along the main road.

The authors [5] point out that at unsignalized pedestrian crosswalks, significant traffic delays are created by pedestrians waiting to cross directly on the roadway, forcing drivers to brake urgently. Therefore, the authors recommend strictly regulating the places allowed for pedestrians to wait on the roadway.

Analysis of pedestrian behavior is one of the most difficult issues in studying the interaction of traffic and pedestrian flows. In a study [6], the behavior of pedestrians when crossing unsignalized pedestrian crosswalks was studied. Roundabouts were investigated here. It was determined that pedestrians who crossed the roadway on the main street, where higher traffic volumes were observed, violated traffic rules less. In addition, the authors include older people and those who crossed a wider roadway into this category. As for violations of traffic rules on secondary roads, they mainly occurred because people had a long way to go to the pedestrian crosswalk.

The authors [7] investigated the effectiveness of relocating pedestrian crosswalks from the intersection zone to the street section between two intersections. From the view of transport, this scenario is efficient, but the authors agree that the absence of pedestrian crosswalks at the intersection will encourage pedestrians to cross the roadway in unauthorized places with violation of traffic rules.

In general, the issue of pedestrian accessibility is quite relevant, especially in the case of roundabouts, since they occupy large areas of the road network. In addition, pedestrians create obstacles in the movement of traffic since the latter must stop before the pedestrian crosswalks for priority passage of pedestrians through the roadway. Such situations create delays in the movement of cars and reduce the capacity of the roundabout. Thus, the authors [8, 9] indicate that the presence of unsignalized pedestrian crosswalks immediately before the roundabout, especially when there is only one traffic lane, significantly reduces the capacity of these lanes when exiting the intersection. In addition, vehicles that exit the intersection and are forced to stop before the pedestrian crosswalk block traffic on nearby approaches to the intersection. The solution is to move the pedestrian crosswalks outside the roundabout, which, according to the authors, increases the capacity of the traffic lane when exiting the roundabout by 10 % [8].

The authors [10–12] also studied the capacity, but on the approach to roundabouts, taking into account the movement of pedestrians at unsignalized pedestrian crosswalks. The authors [10] studied the conditions under which pedestrians are allowed to move through the territory of a roundabout. The results showed a negative impact of increasing the pedestrian volume on the capacity of approaches to a roundabout. For example, data are provided that with the same traffic volume of 500 p.c.u./h, the capacity in the absence of pedestrians and with their volume of 350 ped./h is reduced by more than half.

The authors [13, 14, 15] concluded that safety islands at unsignalized pedestrian crosswalks before roundabouts makes the crosswalk safer and more predictable for pedestrians. In addition, the authors [13] point out that with a dividing line, pedestrians can cross the roadway outside the pedestrian crosswalk. If there is no safety island, pedestrians cross the roadway more carefully and in compliance with traffic rules. Therefore, the authors advise, along with the installation of safety islands, the installation of pedestrian fences to limit the access of pedestrians to the roadway outside the designated space. The authors of [16] generally point to the positive effect of applying various solutions, such as a flashing yellow signal, safety islands, and the introduction of traffic light signaling, on increasing pedestrian safety at roundabouts.

As for the implementation of traffic light control at roundabouts, the results of studies of the effectiveness of installing traffic lights at pedestrian crosswalks before roundabouts using a cellular automaton model are given in [17]. Two options were considered: a traffic light with a call button for pedestrians and a conventional traffic light with fixed-time control. It has been determined that with high volumes of traffic and pedestrians, it is more appropriate to install a traffic light with a call button since, in such a case, lower values of delays for transport are observed. Implementing traffic signals is generally ineffective solution at low traffic and pedestrian volumes. The authors also point out that pedestrians create obstacles for cars when exiting a roundabout, even at low pedestrian volumes. The authors [18] propose the arrangement of an adjustable stepped pedestrian crosswalk to reduce traffic delays at roundabouts. Its essence is that at the entrance to the intersection, the pedestrian crossing is located closer to the central island than at the exit from the roundabout. The authors also suggest implementing traffic light control with priority given to pedestrians if their volume is low and to vehicles if pedestrian volume increases.

4. RESEARCH RESULTS

The intersection of Kulparkivska – Vyhovskoho – Volodymyra Velykoho Str. was chosen to study the influence of pedestrian flows on vehicle delays before roundabouts. PTV VISSIM software was used to simulate traffic and pedestrian flows. All the streets on the approaches to the intersection are arterial streets with two lanes in each direction.

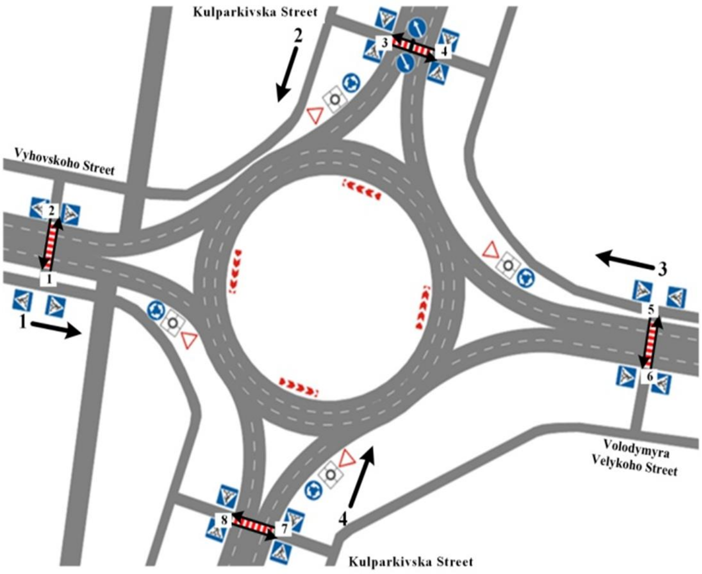

Fig. 1. Scheme of researched roundabout

There are several points of attraction nearby – office premises and a shopping center. Therefore, high values of traffic and pedestrian volumes are observed. There is an unsignalized pedestrian crosswalk without safety islands at each approach to the intersection. The only existing safety island is present at the approach to the roundabout from the side of Kulparkivska Street in the direction of the city center. The intersection is large in area – the radius of the central island is 34.1 m, which makes it possible to classify the roundabout as large, according to the classification of roundabouts [1]. The scheme of the roundabout, drawn in the PTV VISSIM software, with located road signs, is shown in Fig. 1.

At the intersection, field studies of traffic and pedestrian volumes during the peak (morning peak period – from 9:00 to 10:00, lunch peak period – from 13:00 to 14:00 and evening peak period – from 18:00 to 19:00) and off-peak (from 11:00 to 12:00) periods were carried out. Summary values of traffic volumes for each peak and off-peak period are given in Table 1, the pedestrian volumes – in Table 2.

Here, we can observe higher traffic volumes during the morning and the evening peak period, and the value of the morning peak volumes is higher by 8–10 %, which may be related to the regulated start of the working day. The value of traffic flow volume in the lunchtime peak period is closer to the off-peak volumes; however, as expected, the peak volumes in the lunchtime period are higher, and the difference is approximately 31–33 %.

Table 1

Results of the study of traffic volumes at researched roundabout

Period of the day	Values of traffic flow volumes at each approach to roundabout, p.c.u./h			
	No. 1	No. 2	No. 3	No. 4
Morning peak period	1355	1519	1468	1189
Off-peak period	682	761	725	583
Lunchtime peak period	897	1014	969	779
Evening peak period	1256	1397	1361	1079

Table 2

Results of the study of pedestrian volumes at researched roundabout

Period of the day	Values of pedestrian flow volumes at each approach to roundabout, ped./h							
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Morning peak period	167	177	151	159	143	149	178	171
Off-peak period	114	111	109	122	112	121	109	128
Lunchtime peak period	149	172	133	141	128	152	169	144
Evening peak period	159	181	141	155	138	169	168	147

As we can see, the distribution of pedestrian flows by direction is uniform; there are no more or less busy directions at the roundabout. Regarding the distribution of volumes between periods of the day, here we see a slight difference between the number of pedestrians who cross the roadway during the lunchtime and evening peak periods. Such a difference between the distribution of volumes between traffic and pedestrian flows can be explained by the fact that people are more inclined to go out for lunch during their lunch break to establishments which are located within walking distance. In addition, during this period, classes end in most educational institutions, and pupils or students return home. The highest values of pedestrian volumes, as well as for traffic flows, are observed in the morning peak period.

Based on the results of field studies, a model of the studied roundabout was developed in the PTV VISSIM software environment. After simulating traffic flow movement at the intersection, we determined the average delay at the intersection per vehicle and the average and maximum length of the queue, which is formed under the existing traffic conditions at the studied roundabout. The average values are given for all approaches to the roundabout together, as the results of field studies show insignificant differences in the traffic volumes at different approaches. The results of the traffic flow simulation are given in Table 3.

Table 3

Results of traffic flow simulation under existing traffic conditions taking into account pedestrian movement

Period of the day	Average delay per one vehicle, sec	Average length of vehicles queue, m	Maximum length of vehicles queue, m
Morning peak period	15.94	25.9	74.0
Off-peak period	11.02	19.9	64.1
Lunchtime peak period	15.01	23.9	70.9
Evening peak period	14.99	25.3	69.3

According to the simulation results, there is a correspondence between the traffic volume and the values of the average delay and the length of the queue of vehicles, as well as their maximum queue length at the approaches to the intersection. The difference in the values of the average delay per vehicle in the lunchtime and evening peak periods is less than 1 %, and the average and maximum queue lengths are 5 and 2 %, respectively. The difference in the values of the indicators for the morning and evening peak periods is 5–8 %. The values of the simulation results for the off-peak period are the lowest, which also corresponds to the field studies' results.

Traffic simulation was conducted at the studied roundabout for three options for arranging pedestrian crosswalks to assess the impact of pedestrians crossing the roadway at an unsignalized pedestrian crosswalk on the delays of vehicles approaching a roundabout. These options are:

– option 1: arrangement of safety islands on an unsignalized pedestrian crosswalk;
– option 2: arrangement of underground pedestrian crosswalk on all approaches to the roundabout, connecting them to each other under the central island;
– option 3: implementation of adaptive traffic light control with a call button for pedestrians.

Simulation results are given in Fig. 2–4.

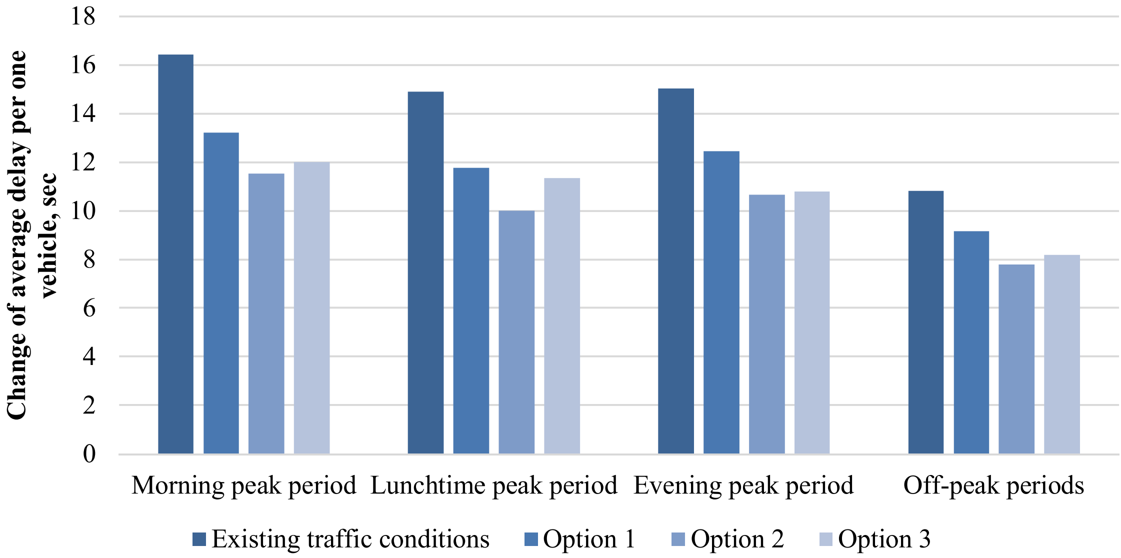

Fig. 2. Change of average delay per one vehicle depending from the option of pedestrian crosswalk arrangement at roundabout

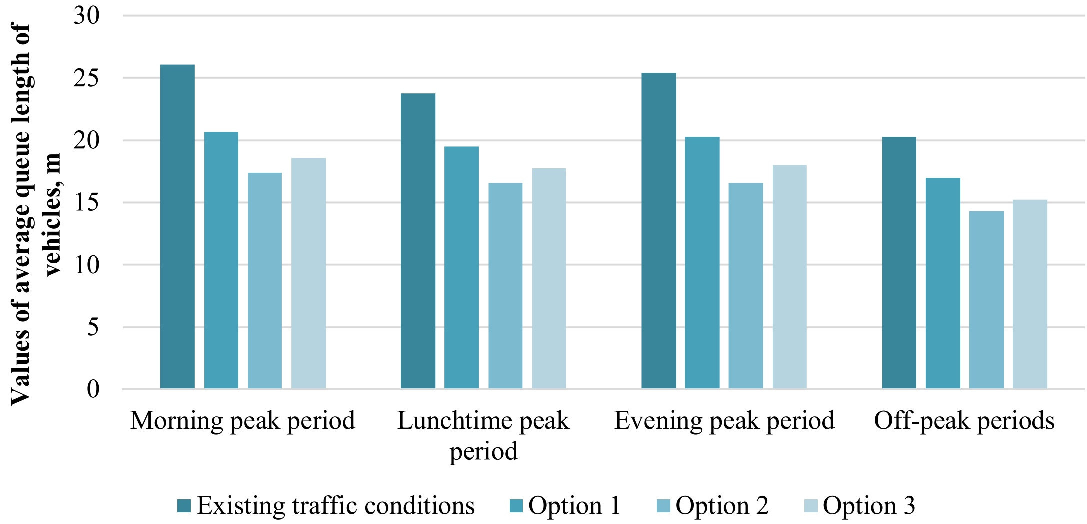

Fig. 3. Change of average queue length of vehicles depending from the option of pedestrian crosswalk arrangement at roundabout

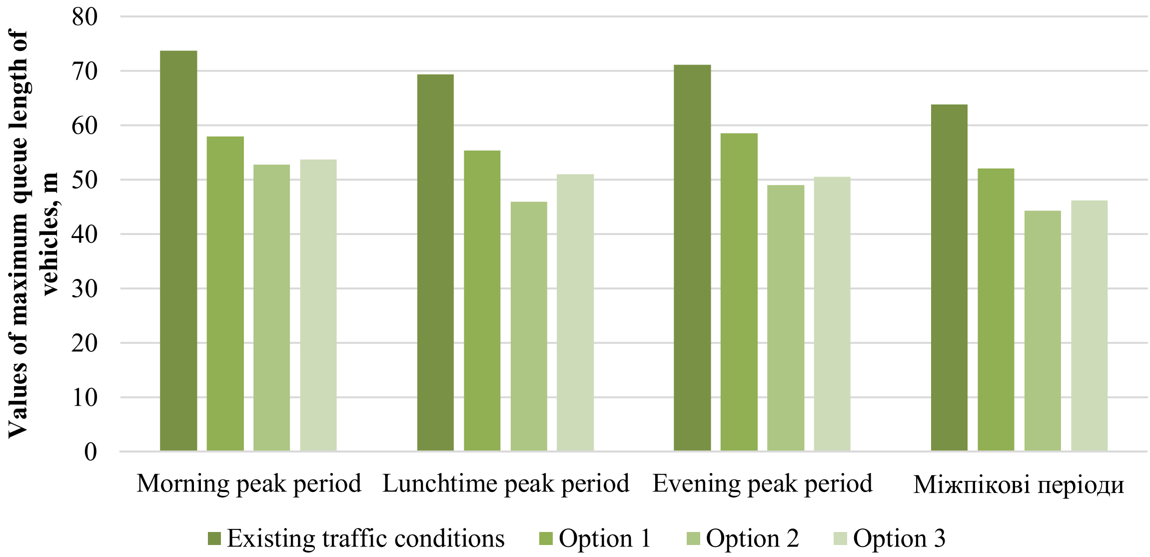

Fig. 4. Change of maximum queue length of vehicles depending from the option of pedestrian crosswalk arrangement at roundabout

We can observe the tangible impact of changing the traffic organization at pedestrian crosswalks on the delays of vehicles before a roundabout. The arrangement of an underground pedestrian crosswalk has the most significant effect since, in this case, there is an absence of influence of pedestrians on the movement of vehicles on the approaches to the roundabout. The reduction in delay compared to existing traffic conditions is 28–33 %, depending on the period of the day. The delay for the second option ranges from 7.8 to 11.5 sec, which, in fact, is a delay due to the significant traffic volume at the intersection.

As for the first option for arranging the pedestrian crosswalks, i.e. adding safety islands – here, the delay reduction is 15.4–21 % compared to the existing traffic conditions. The difference between the traffic delay under the existing conditions and the third option is 23.9–28.2 %, depending on the period of the day.

The difference in delay reduction between the first and second options of arranging pedestrian crosswalks is 10.3–12.6 %, and between the first and third option – 2.9–11.1 %. It is worth noting that the difference in delay between the second and third options is less than one second; the exception is the lunchtime peak period – here, the difference is larger in favor of the second option. It can be explained by the fact that, under existing traffic conditions, at much lower traffic volumes, pedestrian flows have almost the same volumes as in other peak periods. Therefore, eliminating pedestrian crosswalks and replacing them with underground ones significantly improves traffic conditions at the intersection.

As for the average queue length, in general, the situation here corresponds to the results of the average delay per vehicle. The decrease in the average queue length compared to the existing traffic conditions is by 16.3–20.8 % with the first option of arranging the pedestrian crosswalk, by 29.4–33.2 % in the second option, and by 24.9–29 % with the third option.

The decrease in the maximum queue length is 11.83–15.8 m, or 17.6–21.4 % – with the first option of arranging pedestrian crosswalks compared to the existing traffic conditions; 19.56–21.04 m, or 28.5–33.7 % – with the second option; 17.64–20.55 m, or 26.4–28.9 % – with the third option. It is worth noting that with somewhat smaller values of the maximum queue length in the evening peak period compared to the morning peak for the existing traffic conditions, with the first option of arranging the pedestrian crosswalk, the values of the maximum queue length in the evening period are somewhat higher than in the morning peak period.

In general, we can say that, compared to the third option for arranging pedestrian crosswalks, the second option has not have much lower values of the average delay per vehicle and the average and maximum length of the queue. The exception is the lunchtime peak period, but here, the difference is due to the presence of many attraction points, which causes the relatively high values of pedestrian volumes. Such a situation allows us to state that it is more appropriate to use the third option, taking into account the high cost of construction of underground pedestrian crosswalks and the obvious advantage of surface crosswalks over underground ones for the population with reduced mobility.

The difference in the values of the maximum queue length for the first and third options for arranging the crosswalks is for the morning peak period – 5.7 %, for the afternoon peak period – 6.3 %, for the evening peak period – 11.3 %, and for the off-peak period – 9.1 %. This difference can be explained by the fact that the presence of safety islands allows pedestrians to cross the road more confidently, sometimes violating traffic rules, which is confirmed by the analysis of literary sources. The larger differences between options 1 and 3 in the off-peak and evening peak periods, in our opinion, are due to the peculiarity of the location of the intersection in the area of a large number of attraction points, which means a constant flow of pedestrians who want to cross the roadway.

Therefore, taking into account the results of modeling traffic and pedestrian flows at a roundabout and its impact on traffic safety, we can point to the feasibility of implementing adaptive traffic light control with a call button for pedestrians. In further research, however, it is worth investigating the impact of such measures on the traffic efficiency directly at and when exiting the roundabout.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

A roundabout in one of the residential areas of Lviv city was chosen for the study. The intersection is equipped with unsignalized pedestrian crosswalks from all approaches to the roundabout. At these crosswalks, except for one, there are no safety islands. In addition, there are significant traffic and pedestrian volumes at the roundabout. The results of field studies showed the usual increase in the traffic volume in the morning and evening peak periods. As for pedestrian flows, the difference in pedestrian volumes in all peak periods, including lunchtime, is not large because of the many attraction points near the intersection.

Traffic flow simulation was carried out under the existing traffic conditions and for three options for the arrangement of pedestrian crosswalks: arrangement of safety islands at pedestrian crosswalks, arrangement of underground pedestrian crosswalks, and implementation of adaptive traffic light control with a call button for pedestrians. The average delay per vehicle and the average and maximum queue length are determined. The average delay under existing traffic conditions, depending on the period of the day, is 11.02–15.94 s; average queue length – 19.9–25.9 m; the maximum queue length is 64.1–74 m.

The arrangement of safety islands at pedestrian crosswalks made it possible to reduce the delay per vehicle by 15.4–21 %, the average queue length by 16.3–20.8 %, and the maximum queue length by 17.6–21.4 %. The efficiency of the construction of the underground pedestrian crosswalk was 28–33 % higher than the existing traffic conditions when finding the delay per vehicle, 29.4–33.2 % higher when finding the average queue length, and 28.5–33.7 % higher when finding the maximum queue length. Simulation of the implementing the adaptive traffic light control showed a decrease in the delay per vehicle by 23.9–28.2 %, the average queue length – by 24.9–29 % and the maximum queue length by 26.4–28.9 %. An insignificant difference in the results between the second and third options for the arrangement of pedestrian crosswalks and significant financial costs for the arrangement of the second option, made it possible to reject it as the least effective. A decision was made on the feasibility of implementing adaptive traffic light control with a call button for pedestrians, taking into account the results of the reduction of the delay per vehicle and the average and maximum length of the queue for the first and third options for the arrangement of pedestrian crosswalks, as well as traffic safety.

Further research will be aimed at verifying the effectiveness of implementing such measures on traffic flows directly at the circulating flow of the roundabout, as well as when traffic flow exits the roundabout.

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ВПЛИВ ПІШОХІДНИХ ПОТОКІВ НА ЗАТРИМКИ ТРАНСПОРТУ ПЕРЕД САМОРЕГУЛЬОВАНИМИ ПЕРЕХРЕСТЯМИ

Анотація. *У роботі розглянуто саморегульоване перехрестя, розташоване у житловому районі м. Львова. На локації розміщено багато точок притягання, тому інтенсивності транспортних та пішохідних потоків високі. На усіх підходах до перехрестя наявні нерегульовані пішохідні переходи, з яких на трьох відсутні острівці безпеки. Проведено натурні дослідження зі збиранням первинних показників транспортних та пішохідних потоків у пікові та міжпікові періоди. За допомогою програмного забезпечення PTV Vissim визначено затримки транспортних потоків на підходах до саморегульованого перехрестя за реальних умов руху. Запропоновано три варіанти влаштування пішохідних переходів на підходах до саморегульованих перехресть. Перший варіант передбачав облаштування острівців безпеки на всіх пішохідних переходах. Другим варіантом було облаштування підземних пішохідних переходів. Третій варіант – впровадження адаптивного світлофорного регулювання з пристроєм виклику для пішоходів. Здійснено моделювання руху за усіх трьох запропонованих варіантів із визначенням затримки, яка припадає на один транспортний засіб, значень середньої та максимальної довжини черги транспортних засобів на підходах до саморегульованого перехрестя. Усі три варіанти показали кращі результати зменшення транспортної затримки, ніж за нинішніх умов руху. Проте спостерігалися затримки, спричинені самим транспортним потоком. Ці затримки визначено за результатами моделювання другого варіанта. У цьому випадку значення транспортної затримки є найнижчими. Найвищі значення затримок, порівняно з іншими варіантами, спостерігалися за першого варіанта. Визначено переваги та недоліки кожного із варіантів облаштування пішохідних переходів. Подано рекомендації щодо доцільності розміщення різних видів пішохідних переходів на підходах до саморегульованого перехрестя.*

Ключові слова: *транспортний потік; пішохідний потік; безпека руху; моделювання руху; нерегульований пішохідний перехід.*