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Article

Reconstructing Intersection Conflict Zones: Microsimulation-Based Analysis of Traffic Safety for Pedestrians

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Abstract: According to statistics from the World Health Organization, traffic accidents are one of the leading causes of death among children and young people, and statistical indicators are even worse for the elderly population. Preventive measures require an approach that includes analyses of traffic infrastructure and regulations, users' traffic behavior, and their interactions. In this study, a methodology based on traffic microsimulations was developed to select the optimal reconstruction solution for urban traffic infrastructure from the perspective of traffic safety. Comprehensive analyses of local traffic conditions at the selected location, infrastructural properties, and properties related to traffic users were carried out. The developed methodology was applied and tested at a selected unsignalized pedestrian crosswalk located in Osijek, Croatia, where traffic safety issues had been detected. Analyses of the possible solutions for traffic safety improvements were carried out, taking into account the specificities of the chosen location and the traffic participants' behaviors, which were recorded and measured. The statistical analysis showed that children had shorter reaction times and crossed the street faster than the analyzed group of adult pedestrians, which was dominated by elderly people in this case. Using microsimulation traffic modeling (VISSIM), an analysis was conducted on the incoming vehicle speeds for both the existing and the reconstructed conflict zone solutions under different traffic conditions. The results exhibited a decrease in average speeds for the proposed solution, and traffic volume was detected to have a great impact on incoming speeds. The developed methodology proved to be effective in selecting a traffic solution that respects the needs of both motorized traffic and pedestrians.

Keywords: traffic safety; child pedestrians; elderly pedestrians; conflict zone reconstruction; incoming speed; traffic microsimulation

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1. Introduction

Statistics related to road traffic safety published regularly by the European Commission [1] show a substantial difference in road safety levels among EU countries. Sweden is the country with the best indicator, with 22 deaths per 100,000 inhabitants, but Croatia had 71 deaths per 100,000 inhabitants in 2023, which renders it one of the countries with the worst indicators within the EU.

According to the Bulletin on Road Traffic Safety in the Republic of Croatia from 2023 [2], in the last ten years, an average of 32,063 traffic accidents occurred on Croatian roads per year, of which almost one-third resulted in casualties. In the same period, an average of 299 people died in traffic accidents per year, and it is estimated that around 5% of the victims, mostly young people, remained permanently disabled. If we compare casualties by traffic type, in the EU, car occupants suffer the most (45%), followed by pedestrians (18%), motorcyclists (16%), and cyclists (10%). Croatian statistics do not provide an overview of drivers by traffic type; thus, the comparable data are the share of pedestrians killed in 2023, which is slightly lower than that in the EU and amounts to 16.5%. In Croatia, pedestrians are killed to a significantly greater extent in settlements (66%), and, in 2023, 44% of pedestrians killed were over 65 years old. The number of fatally injured child pedestrians varies by year; in 2023, four children and young people under the age of 17 died in Croatia, which was about 9% of the total number of pedestrians killed during that year.

Based on the Croatian Law on Traffic Safety [3], the protection of pedestrians at unsignalized pedestrian crossings is covered by provisions that bind both drivers and pedestrians. According to the law, drivers are obliged to move upon the approach of a marked pedestrian, crossing at a speed that allows them to stop in case a pedestrian is on the crossing or stepping on the roadway. At the same time, the pedestrian should assess whether they can cross the street by estimating the speed and distance of the approaching vehicle before stepping onto the road. Given these rules, which do not oblige the driver to stop if a pedestrian is waiting at or approaching a marked crosswalk, the approaching vehicle's speed becomes very important for pedestrian safety.

A factor that is extremely important when discussing a conflict between a moving vehicle and a pedestrian is the specific speed at which the conflict occurred (impact speed) because it directly affects the severity of pedestrian injuries. During the period from 1980 to 2017, studies on traffic accidents involving pedestrians were conducted in various countries (UK, USA, Germany, Republic of Korea, China, and Japan), in which different age groups were analyzed—in addition to the consequences that resulted and the conditions by which they occurred [4–6]—to determine the pedestrian fatality risk as a function of car impact speed. Analyses of the results of available studies [4–6] suggest that an impact speed of 30 km/h has a risk of fatality of around 5% on average, and this risk increases to 13% at an impact speed of 40 km/h and 29% at 50 km/h [6]. In Croatia, the regulated speed on city roads, unless otherwise specified, is 50 km/h, and 30 km/h zones are still not accepted as solutions.

Speed control on urban roads, which aims to reduce the number and consequences of traffic accidents, is achieved by one or a combination of several types of measures. Measures can vary between legal solutions (repressive measures) [7]; warnings and radar implementation [8–11]; and infrastructural interventions, such as road surface elevation [12], raised medians [13,14], and refuge islands [15–20].

The safety of pedestrian traffic also depends, to a large extent, on the behavior of the pedestrians themselves and their ability to assess the traffic situation, in addition to the decisions they make in places where they are potentially subject to conflict with vehicles—pedestrian crosswalks [21–25]. Children and the elderly are perceived as particularly vulnerable groups of pedestrians due to their reduced ability to assess the situation and/or reduced mobility [26–28].

Analyses of existing research (Section 2) show that in the complex relationship between traffic participants, infrastructure, and environmental conditions, it is necessary to look at the situation through the analysis of individual elements related to road traffic safety and their interrelationships. As a tool for traffic safety analysis, different methods and their combinations can be used [29–31]. When comparisons and selections of possible solutions are carried out according to the conclusions of available research [32–35], the traffic microsimulation method is appropriate.

The aim of this paper is to define a methodology for improving the conditions of pedestrian traffic safety based on an analysis of the actual micro-location through an analysis of the behavior of all traffic participants and the impact of possible infrastructure solutions on vehicle speed, which has been established as a critical safety parameter [3–5]. The proposed methodology was applied to the analysis of the selected conflict zone within an urban four-lane at-grade intersection. The selection of this particular crosswalk was motivated by the occurrence of traffic accidents involving pedestrians at the location and measurements of operational speeds that were significantly higher than the permitted speed. Pedestrian recordings and automatic measurements of the number and speed of vehicles were performed in real traffic conditions. Parameters that had a statistically significant impact on pedestrian traffic, including those related to motor traffic, were determined. Several solutions for the reconstruction of the intersection were proposed, with the primary goal of reducing vehicle speeds. The effects of the proposed solutions were analyzed. Given that the development of the surrounding zone is expected, the impact of the increase in traffic volume that can be realistically expected (from 100% to 150%) was analyzed. Increases in traffic volume by 200% and 250% were also analyzed in order to theoretically investigate the relationship between traffic volume increase and speed. For the analysis of the proposed solutions, the traffic microsimulation method was used via the creation of models in the VISSIM 11 software package. The application of the developed methodology to the described case study enables conclusions about its advantages and limitations.

This study is organized as follows. After providing an introduction in Section 2, an overview of the available research is presented. In Section 3, the materials and methods used in this research are described. Traffic analyses are presented in Section 4. Section 5 provides the results and discussions, and, finally, in Section 6, the conclusions, together with limitations and further research plans, are presented.

2. Overview of the Available Literature

This review of the available literature includes sources relevant to the effectiveness of different infrastructural speed control solutions and the behavior of the pedestrian types examined in this research—children and the elderly.

2.1. Traffic-Calming Measures

The application of traffic-calming measures depends on different factors, such as traffic safety analyses based on accidents or measured operational speeds, in addition to overall traffic conditions, location in the urban area, expected users, etc.

Reducing the permitted speed on a certain section of a road can be considered a mild measure of speed reduction. Studies that analyze the influence between changes in speed limits and changes in average or operational speeds found that when only the speed limit was decreased, the effect on speed was moderate. For a decrease of 10 km/h, the average speed decreased by approximately 2–3 km/h [7].

Analyses of the effects of panels indicated that their effect varied according to the country and location and that the panel measure had an effect only on a stretch of the road where it was directly placed [8,9]. The effects of the introduction of Tempo-30 zones around school and playground zones in Calgary, Canada, were analyzed at 27 locations to determine what affected the operational (V85) and average speeds at these locations. Among the selected parameters (e.g., zone type, presence of children, roadway width, presence of speed monitoring device, road category, type of control), the presence of a warning device at a location near schools had the greatest impact on speed reduction [10].

The authors of [11] presented a study of the implementation of various traffic-calming measures in several cities in the north of Spain. The impact of infrastructural solutions, such as a raised pedestrian crosswalk, narrowing of the traffic lane, and installation of a radar speed camera, was analyzed based on 50-percentile and 85-percentile speed data. The raised crosswalk was determined to be a very effective traffic-calming measure as it caused a speed decrease of approximately 9–10 km/h, and a reduction effect was also visible outside the measurement area. Radars, on the other hand, only had an impact on the location at which they were installed.

The authors of [12] analyzed various solutions implemented in Sweden to reduce speeds at the entrances of Tempo-30 zones. As a measure of speed control, vertical (speed table and raised junction) and horizontal (roundabouts, mini roundabouts, and roundabouts with offset or skewed approaches or both) treatments were applied and analyzed. Changing the road surface elevation proved to be the most effective measure of speed reduction among the analyzed five types.

The influence of the built environment, pedestrian infrastructure, and road infrastructure on pedestrian safety was analyzed with respect to 20 roadways, and a total of 315 pedestrian crashes in two Portuguese cities (Braga and Guimaraes) were reported [13]. It was shown that longer distances between crosswalks significantly influenced the increase in the number of traffic accidents, while the presence of raised medians increased the vehicle–pedestrian crash frequency.

Studies investigating the use of the central pedestrian islands as a measure to increase pedestrian traffic safety have yielded mixed results. The results of research conducted in Japan on 86,406 traffic accidents involving vehicle–pedestrian collisions [14] showed that in intersection crashes, the installation of stop signs, medians, three-light traffic signals, and innovative flashing and pedestrian-controlled traffic signals may reduce the fatality risk of pedestrians.

The results of research conducted in Tehran showed a statistically significant reduction with respect to the mean speed of vehicles and the fatal accident number of vehicle–pedestrian collisions after the application of central pedestrian islands [15]. The implementation of refuge islands at pedestrian crosswalks has reduced the number of fatalities for pedestrians by 64%, and research on irregular movements according to the type of crosswalk shows that crosswalks equipped with flashing amber lights, refuge islands, and traffic lights induce substantially more appropriate behavior in car drivers [16].

Different engineering countermeasures designed to increase the conspicuity and visibility of pedestrian crosswalks at roundabouts have been tested to assess their impact on road safety. These countermeasures included the installation of a median refuge island, the displacement of zebra markings in advance of the intersection, and the placement of "Yield here to pedestrians" vertical signs. The safety evaluation was performed using before–after speed and driver's eye movement analyses. The results showed that the reduction in approaching speeds after the implementation of the measures was statistically significant; the zebra markings and median refuge island were the most glanced-at elements and the division island significantly lowered distractions in the gaze behavior of drivers [17].

Research on the impact of splitter islands on pedestrian safety at roundabouts using surrogate safety measures, conducted in Japan [18], showed that the application of splitter islands exhibited significantly safer performances with respect to all traffic flow directions at roundabouts. The significance of geometric shapes and the driver's vision was investigated in [19], and the results showed that pedestrian refuge islands imposing a symmetric lateral shift of 1 m that are not accompanied by street furniture have no significant bearing on speed reduction within their vicinity. This was observed irrespective of their location along the stretch of road in the village and the geometry of associated pavement markings. Conversely, an asymmetric lateral shift in the travel alignment generated by the refuge island located on one side of a road's centerline induces considerable speed reductions, but this only occurs when the driver sees residential buildings near the road. The authors of [20] investigated the effect of various mid-block tools, such as refuge islands, speed tables, and raised pedestrian crosswalks, in reducing speed. The findings were as follows: the presence of refugee islands themselves does not significantly reduce the speed of vehicles.

2.2. Pedestrian Traffic Behavior

A study conducted in Edinburgh [21] investigated pedestrian crossing behavior at a mid-block crosswalk with a refuge island, which was located in an urban area with high observed pedestrian accident frequencies. The results showed that the critical gap for crossing from the median to the curb was much shorter than that from the curb to the median. Pedestrians appeared to be less cautious when crossing from the median to the curb as they were more likely to accept a shorter traffic gap. Research conducted in Poland showed which elements affect the effectiveness of a division island as a traffic-calming measure: free view, visibility of a pedestrian on the right side of the island, and refuge island surroundings [22].

Research conducted in developed countries shows that elderly people are at greater risk when crossing the street because they have a harder time evaluating their surroundings [23].

Previous research carried out by the authors in relation to the behavior of children in pedestrian crossing conflict zones showed that the reaction time of younger children is statistically significantly longer than the reaction time of adults, but, for children over 12 years of age, this difference was no longer statistically significant [28]. The use of mobile phones, which occupy visual attention, is a statistically significant influencing factor with respect to the reaction times of children [36], young people [29], and pedestrians [36]. It was also shown that the age of the child, as well as movement, has an influence on the behavior of children at pedestrian crosswalks with [36] and without traffic lights [37]. For the infrastructural elements, children's behavior was significantly influenced by the length of the zone where they were potentially exposed to conflict with vehicles; this is called the conflict zone. With respect to pedestrian crosswalks without traffic lights, preliminary results showed that the approaching vehicle's speed also has an impact on children's behavior [37].

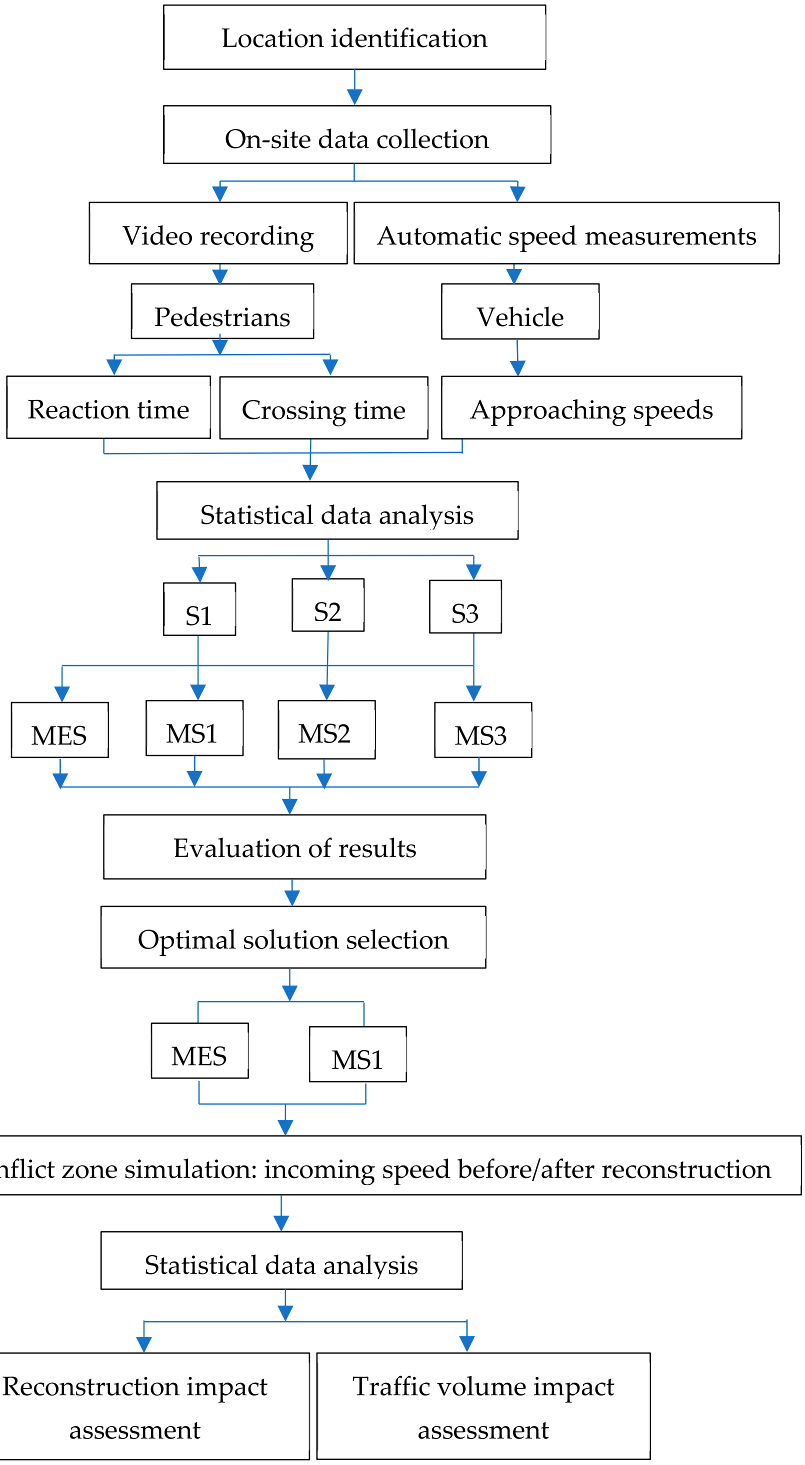
Analyses of the behavior and awareness of road traffic hazards among pedestrians in Poland for those under 18 and over 65 years [38] were conducted, using surveys on a sample of 265 participants under the age of 18 and 357 participants over the age of 65. The results showed that older pedestrians less frequently exhibited dangerous behavior, such as crossing roads in an unauthorized location or using headphones on crosswalks, but they tended to have less awareness of threats from other road users; in particular, they made less correct estimations regarding pedestrian visibility in dusty conditions and driver reaction times compared to respondents under 18 years of age, which was also confirmed by the authors of [23–25]. A risk analysis was carried out in relation to pedestrian behavior with respect to age, time gap, time of day, and vehicle speed [39] and it was found that pedestrian decisions on whether to cross a road safely were made based on the distance between them and approaching vehicles. The study found that elderly pedestrians estimated that they needed the same average time to cross the street as young pedestrians, even though their measured walking speed was significantly lower. It was also observed that pedestrians generally rely extensively on estimations of the distance of the approaching vehicle while simultaneously being insensitive to changes in the speed of approaching vehicles.

3. Materials and Methods

The basic methodological steps proposed in this study are shown in Figure 1.

3.1. Case Study Location

The observed pedestrian crosswalk, which was analyzed according to the proposed methodology, is located on a two-lane eastern driveway of a non-signalized four-lane intersection. The main street is Drinska Street (east–west) and the side street is Krbavska Street (north–south), located in the city of Osijek in Croatia (Figure 2). The intersection is located within the immediate vicinity of an elementary school and high school (east driveway). On the west driveway, there is a home for the elderly and a health center. A school, the Centre for Education for Children with Special Needs and the Cultural Centre of the Hungarian Minority, which includes a kindergarten and primary and secondary schools, is oriented towards the southern driveway. The northern driveway is oriented from the direction of the residential street. There is a large concentration of vulnerable traffic users at the observed pedestrian crosswalk.



Reconstruction solutions (S1, S2, and S3); existing solution model (MES); reconstruction solution models (MS1, MS2, and MS3).

Figure 1. Diagram of the basic methodological steps.

The length of the vehicle–pedestrian conflict zone of the pedestrian crosswalk is 6.4 m and the width of the pedestrian crosswalk is 3.3 m (marked with a blue border in the first image). The observed road comprises two lanes, with the width of each lane being 3.2 m. The geometric design of the conflict zones does not indicate a potential problem. The curbs are lowered; thus, there is no indication of an accessibility problem. The pedestrian crossing is marked with horizontal and vertical traffic signals. The vertical sign is a pedestrian crossing information sign and is located two meters from the stop line in the east direction.

The visibility provided is much greater than the legally prescribed stopping distance, and the approaching lane is straight, as observed in Figure 2. The design and geometric elements of the pedestrian crossing do not indicate a potential safety problem, but the road elements allow for driving at higher speeds than the set administrative limit of 50 km/h.

Figure 2. Observed pedestrian crosswalk [34].

According to Traffic Police data records, from 2017 to 2022, there were 7 traffic accidents involving pedestrians at the observed pedestrian crossing (Table 1).

Table 1. Number of traffic accidents with pedestrians at the observed pedestrian crossing [34].

Year	The Age of the Pedestrian	Injuries	Cause of the Accident	The Fault of Pedestrians
2017	18	Minor injuries	Deprioritization	No
2018	16	Minor injuries	Deprioritization	No
2018	13	Serious injuries	Deprioritization	No
2020	80	Minor injuries	Deprioritization	No
2021	15	Minor injuries	Deprioritization	No
2022	12	Minor injuries	Deprioritization	No
2022	10	No injury	Running	Yes

Among the pedestrians involved in traffic accidents, the majority were children, and one was an elderly pedestrian. Analyses of the traffic accident causes showed that in most cases, the denial of the right of way of pedestrians was the cause of the accident. This was, in turn, a consequence of inappropriate incoming vehicle speeds. Statistics show that there were no pedestrian fatalities within the observed time period, but the frequency of traffic accidents indicates a safety problem.

The measured operating speed of the incoming vehicle (V85) was 63 km/h, which exceeds the administrative speed limit.

The observed pedestrian crossing, in addition to historical traffic accident and operational speed data, was chosen because it is located on a pedestrian path towards the Clinical Hospital Center, the construction of which is expected in the near future, which will have a further impact on the traffic flow of pedestrians and vehicles.

3.2. Database Formation

Two field measurement databases and a database based on the results of microsimulation traffic modeling were formed (Figure 1).

The first database separately contained data on the behavior of child and adult pedestrians in the conflict zone, which were analyzed. The selected dependent variables were the reaction and crossing times of pedestrians. Both datum types were gathered from video recordings of pedestrians in real traffic conditions. Reaction times were established as the time from the arrival of the pedestrian at the pedestrian crosswalk to the point in time during which they checked for traffic. The crossing time was established as the time between stepping off the curb at a pedestrian crosswalk and stepping onto the curb on the opposite side of the road with both feet. The basic characteristics of pedestrian behavior that were collected in the field were used as input data for the formation of a microsimulation traffic model.

The second database contained data from an automatic traffic counter and included traffic volume, traffic structure, and incoming vehicle speeds. The collected data were used to form microsimulation models of the existing conflict zone and variant solutions for reconstruction. By analyzing and comparing variant solutions according to flow indicators (delays and queue lengths) and safety parameters, the optimal variation solution for reconstruction [34] was selected, which was used for a detailed analysis and comparison of incoming vehicle speeds in different traffic scenarios.

The third database contained data on incoming vehicle speeds obtained using simulation traffic modeling. Microsimulation traffic modeling in VISSIM served as a tool for the analysis of incoming vehicle speeds for the existing conflict zone solution and the selected reconstruction solution. Different vehicle and pedestrian traffic volumes were analyzed in order to assess the impact of reconstruction and increase in traffic volume on incoming vehicle speeds for different infrastructure solutions (before and after reconstruction).

3.2.1. Database: Pedestrians

Field data on pedestrian behavior were obtained via a video camera on Thursday, 14 June 2022, and the results are presented in Table 1 and in more detail in [34]. The peak morning hour was chosen, between 7 and 8 a.m., because the traffic flow of pedestrians was the highest due to the arrival of children at the school.

By analyzing the collected data and the results of existing research [28,36,37], parameters that have an impact on the reaction and crossing times of children and adult pedestrians were selected, and these also included data about the infrastructural solution of the observed crosswalk location.

The databases were separately formed for children and adults according to the input parameters shown in Table 2. The selected dependent variables were pedestrian reaction and crossing times (Figure 1).

Table 2. Measured and observed influencing variables.

	Variables	Data Type	Description	Type of Variable
1.	Age group	Number	Pedestrians divided into age groups according to the following criteria: 1 = < 6 y; 2 = 7–10 y; 3 = 11–14 y; 4 = 15–18 y; 5 = 19–24 y; 6 = 25–40 y; 7 = 41–65 y; 8 = >65 y	Categorical
2.	Gender	0/1	Gender of the pedestrian: girl→0; boy→1	Categorical
3.	Supervision	0/1	Adult supervision for children: NO→0; YES→1	Categorical
4.	Special need	0/1	A pedestrian with difficulties (e.g., motor or visual): NO→0; YES→1	Categorical
5.	Group number	Number	Movement of pedestrians in a group; number of pedestrians in the group; if the pedestrian moves individually, the number is 1	Categorical
6.	Talking on a mobile/ listening to music	0/1	Using a mobile phone without disturbing visual attention: NO→0; YES→1	Categorical
7.	Mobile SMS/Internet	0/1	Mobile phone use with visual distraction: NO→0; YES→1	Categorical
8.	Crossing outside crosswalk	0/1	Crossing the road outside the pedestrian crosswalk: NO→0; YES→1	Categorical
9.	Running	0/1	Crossing the road by running: NO→0; YES→1	Categorical
10.	Checking left	0/1	Checking the traffic situation before crossing the road (left side): NO→0; YES→1	Categorical

Table 2. *Cont.*

	Variables	Data Type	Description	Type of Variable
11.	Checking right	0/1	Checking the traffic situation before crossing the road (right side): NO→0; YES→1	Categorical
12.	Vehicle arrives left	0/1	The arrival of a vehicle towards a pedestrian from the left side of the pedestrian: NO→0; YES→1	Categorical
13.	Vehicle arrives right	0/1	The arrival of a vehicle towards a pedestrian from the right side of the pedestrian: NO→0; YES→1	Categorical
14.	Vehicle stopping left	−1/0/1	The vehicle coming from the left stopped in front of the pedestrian crosswalk: −1 if the vehicle did not approach; 0 if the vehicle did not stop; 1 if the vehicle stopped	Categorical
15.	Vehicle stopping right	−1/0/1	The vehicle coming from the right stopped in front of the pedestrian crosswalk: −1 if the vehicle did not approach; 0 if the vehicle did not stop; 1 if the vehicle stopped	Categorical
16.	Vehicle breaking left	−1/0/1	The vehicle coming from the left slowed down/braked in front of the pedestrian crosswalk: −1 if the vehicle did not approach; 0 if the vehicle did not slow down/brake; 1 if the vehicle slowed down/braked	Categorical
17.	Vehicle breaking right	−1/0/1	The vehicle coming from the right slowed down/braked in front of the pedestrian crosswalk: −1 if the vehicle did not approach; 0 if the vehicle did not slow down/brake; 1 if the vehicle slowed down/braked	Categorical
18.	Total number of children at crosswalk	Number	The total number of children at the crosswalk at the time of observation, who may or may not have been moving in a common group	Continuous
19.	Total number of pedestrians at crosswalk	Number	The total number of pedestrians at the crosswalk at the time of observation, together with child pedestrians	Continuous
20.	Number of cyclists at crosswalk	Number	Number of cyclists crossing the road using the observed pedestrian crosswalk	Continuous

Out of a total of 20 observed variables, 17 were categorical variables. Previous research [37] identified more parameters from the groups: traffic flow (85th percentile speed of incoming traffic flow, average and maximum recorded vehicle speed in the observed hour, the percentage of vehicles that drive faster than the speed limit, vehicle traffic volume, and vehicle traffic flow structure), pedestrian traffic volume, design and geometric characteristics of the conflict zone, the existence of a pedestrian island, horizontal and vertical retarders, and the lengths of the available sight distance, which were constant in this case. The parameters listed apart from those in Table 2 have an impact on pedestrian behavior [37], but this impact can be quantified when the database includes multiple measurements at different pedestrian crossings, which was not the case in this research.

3.2.2. Database of Measured Traffic Volume and Vehicle Speed Data

Field measurements of vehicle traffic were carried out for the observed conflict zone of the crosswalk. Field data of the traffic volume, the structure of the traffic flow, and the speeds of incoming vehicles were collected using an automatic traffic counter (SDR traffic data collector) during the peak hour between 7 and 8 a.m., which was within the same period when pedestrian flow data were collected.

3.2.3. Database of Incoming Speeds Obtained Using Microsimulations

Speed analysis using the VISSIM microsimulation model was carried out for the incoming speeds of cars on the eastern driveway for existing and reconstructed pedestrian crosswalk data; the counted traffic and traffic volume increased from 50 to 250%. There is no continuous traffic counting at the observed location; by comparing the individual counting that was carried out in 2019 and 2022, traffic increased by 37%, which is slightly more than 12% per year. The data should be analyzed as an indicator that is not entirely reliable. In the vicinity of the observed pedestrian crosswalk, the construction of the new Clinical Hospital Center Osijek is planned; this is expected to increase the traffic flow of vehicles by 50%, 100%, and even up to 150% after construction. An increase in traffic of 200% and 250% at the observed location was not expected, but this was used for the purposes of additional theoretical analysis with respect to the impact of reconstruction and increases in traffic volume on the dynamic parameters of vehicular traffic flow.

To model the stochastic nature of traffic flow, VISSIM uses random numbers, distributions, and various mathematical models for different traffic situations. In this particular case, we modeled the interaction between vehicle traffic flows, a single traffic stream, and pedestrian flows. For the car-following model, VISSIM is based on the psychophysical Wiedemann model, and, specifically for urban conditions, the Wiedemann 74 model is used [32,33]. The Wiedemann model assumes that a driver can be in four different driving regimes, which include the following: following, free-driving, closing in, or braking. These are defined by the thresholds that represent the points at which a driver changes driving behavior.

The distance d between two vehicles is computed as follows [34]:

$$d = ax + bx, \tag{1}$$

where ax is the standstill distance

$$bx = (bx\_add + bx\_mult \times z) \times \sqrt{v}, \tag{2}$$

v is the vehicle speed, m/s;
z is a value of range [0,1], which has a normal distribution with a mean of 0.5 and standard deviation of 0.15;
bx_add is the additive part of the desired safety distance;
bx_mult is the multiplicative part of the desired safety distance.

To model pedestrian traffic flow, VISSIM uses a Social Force Model for pedestrian movement. The basic principle of the Social Force Model is to model the elementary impetus for the motion of pedestrians analogously relative to Newtonian mechanics. From the social, psychological, and physical forces, we obtain the total force, which eventually results in an entirely physical parameter named acceleration. These forces arise from the desire of the pedestrian to reach a goal and it is influenced by other pedestrians and obstacles in their environment.

The social force consists of three components [40]:

1. Self-driving force (Fα0): Represents the inner drive of a pedestrian in an ideal state, guiding them towards their desired direction and speed;
2. Human interaction force (Fαβ and Fαi): Represents the interactions between a pedestrian and other pedestrians, including both attractive and repulsive forces;
3. Obstacle force (FαB): Represents the resistance or repulsion from obstacles in the environment.

Classical social force $F_\alpha(t)$ is mainly used to express the physical quantity externalized by the specific inner activity of a person in performing a behavior, which is provided via Equation (3) [40]:

$$F_\alpha(t) = F_\alpha^0\left(v_\alpha, v_\alpha^0 e_\alpha\right) + \sum_B F_{\alpha B}(e_{\alpha'} r_\alpha - r_B^\alpha) + \sum_\beta F_{\alpha\beta}(e_{\alpha'} r_\alpha - r_\beta) + \sum_i F_{\alpha i}(e_{\alpha'} r_\alpha - r_i, t) \tag{3}$$

where

v_α is the actual speed of pedestrian α;
e_α refers to the desired direction of motion;
r_B^α denotes the distance of pedestrian α to obstacle B;

r_α denotes the range of forces acting on pedestrian α.

In the model's input data, several groups of pedestrians were formed in the structure of pedestrian flows, and different movement speeds measured in the field were assigned in the model.

To render the modeling results for the same input data repeatable, a certain value of the random seed always assigned the same random number values to the variables, and the same vehicle arrival scenario was applied, which was important for the repeatability of the experiment; however, this rendered the model quasi-stochastic. In order to obtain model results that were closer to real results in the field, it was necessary to run the simulation more than once, which was achieved by assigning an automatic multi-run that had an initial value of a random seed and a given increment (random number generator step).

For each project solution and traffic volume, an analysis of 10 different scenarios of vehicle arrival was carried out (Figure 3), and, for the databases to be comparable with respect to all traffic volumes, the same 10 scenarios were used (the initial value of the random number generator was 42 and the default increment was 10). The diagram in Figure 3 shows the vehicle generation percentages in the model in minute intervals for one hour of simulation and for each of the 10 observed scenarios. For different traffic volumes, the absolute number of vehicles was different, but their distribution remained the same. A time interval of 60 s was chosen because incoming vehicle speeds were analyzed within the same time interval.

In order to obtain the same amount of data for analyses and comparisons of incoming speeds, a comparison of average speeds was carried out every 60 s of simulation. For one hour of the simulation, 60 data instances of the minute intervals of the average speed per simulation were analyzed, i.e., for the analysis of 10 different vehicle arrival scenarios, 600 min speed data instances were obtained for each infrastructure solution and each traffic volume.

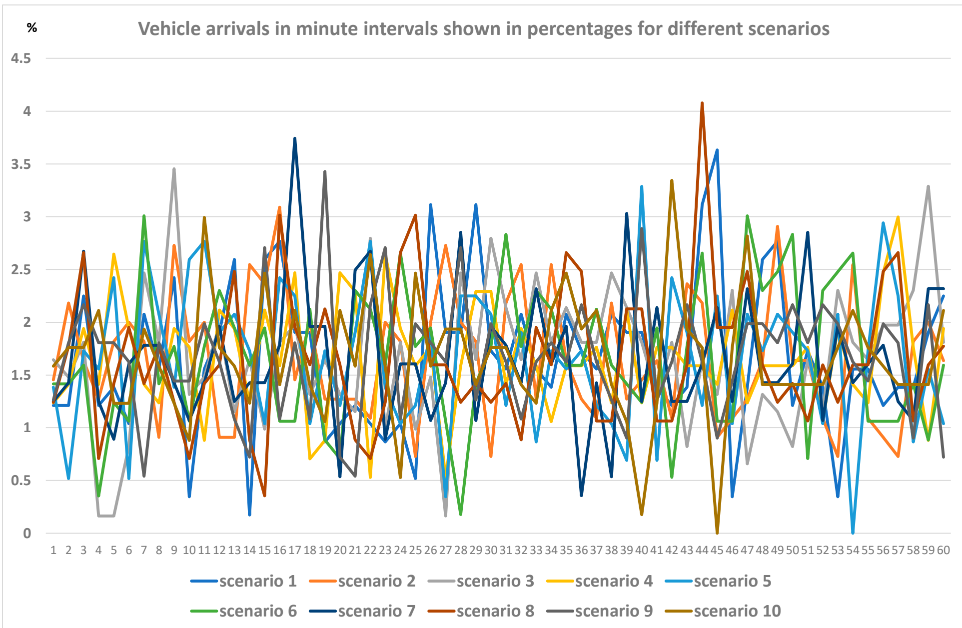


Figure 3. Vehicle arrivals in minute intervals in percentages.

4. Basic Traffic Analyses

4.1. Speed and Traffic Analyses

Data on pedestrian behavior were collected using a video camera, and the incoming speeds of vehicles were measured via an automatic counter placed 20 m from the pedestrian crossing in the east direction.

The field measurement results of traffic volume and traffic flow structure are shown in Table 3, and they are discussed in more detail in [34].

Table 3. Traffic volume on approaches and pedestrian crosswalk measured speeds.

	Traffic Volume					
	Drinska—Main Street				Krbavska—Side Street	
	East–West		East–East		North–South	South–North
Vehicles [veh/h]	195		164		38	63
Pedestrians [ped/h]	108		-		17	72
	Measured speeds of the eastern Drinska approach					
	N	Mean	StDev	V85	Min	Max
Measured speed [km/h]	195	51.50	11.09	63.0	21.00	76.00

Of the total number of vehicles, 89% were passenger cars, 9% were trucks, 1% were buses, and 1% were motorcycles. Of the total number of pedestrians at the observed pedestrian crossing on the eastern approach, 82% were children and adolescents and 18% were adult pedestrians. In the footage, 62 bicycles were spotted on the footpaths on both sides of the main street.

In the child pedestrian groups, 7% were under 10 years of age and 31% were in the 11-year-old to 14-year-old group. Of the total number of pedestrians in the adult population, 37% were over 65 years old and 11% were adult pedestrians with motor disabilities.

By measuring and comparing the incoming speeds in real conditions [34], the speeds of the eastern approach of the main road proved to be critical (Figure 2). Vehicles from the main eastern traffic flow driveway first encountered the pedestrian crosswalk (vehicle–pedestrian conflict zone) and then the vehicle–vehicle conflict zone. For the western driveway, which does not have a pedestrian crosswalk, the opposite was observed; thus, when vehicles encountered the pedestrian crosswalk, the vehicles passed through the vehicle–vehicle conflict zone, which caused a decrease in the homogenization of speeds. Within this paper, the analysis results of the critical flow of vehicles are presented, and the descriptive statistics for the measured speeds of the eastern approach are presented in Table 3.

The mean value of the measured incoming speeds, standard deviation, operating speed (V85), and minimum and maximum measured speeds for the observed peak hour are displayed. Table 3 shows that the operating speed (V85) was 63 km/h, which is 26% higher than the administrative limit. According to the results of the measurement, 56% of drivers drove faster than the administrative limit.

The average speed of the traffic flow or individual traffic stream was the input data for the microsimulation model, which served as the median of the speed distribution for the microsimulation model. In accordance with the stochastic nature of the traffic flow, the model randomly assigned speeds to individual entities from the pool of possible choices, respecting the median and standard deviation. In this manner, different incoming vehicle speeds were obtained, in addition to the actual traffic flow; these were then influenced by interactions with other vehicles, pedestrians, and cyclists, respecting the priority rules assigned to the model.

4.2. Comparison of Traffic Parameters for Conflict Zone Reconstruction Solutions

To improve safety in the observed intersection zone, three solutions have been proposed:

Solution 1 (Figure 4b) of the reconstruction of the conflict zone envisages a pedestrian island and a narrowing of traffic lanes from 2 × 3.2 m to 2 × 2.6 m at the site of the observed pedestrian crosswalk.

Solution 2 (Figure 4c) of the reconstruction of the conflict zone envisages a division island and narrowing of the roadway to 2 × 2.8 m. The division island ends before the conflict zone; thus, the length of the pedestrian crossing is 5.6 m.

Solution 3 (Figure 4d) envisages the reconstruction of the driveway and combines division islands with additional horizontal discontinuities and lane relocation without narrowing the pavement; this is discussed in more detail in [34].

To analyze the impact of reconstruction and the increase in traffic volume on incoming vehicle speeds, four models were formed in VISSIM: the model for the existing pedestrian crosswalk (Figure 4a) and the proposed infrastructural solutions (Figure 4b–d).

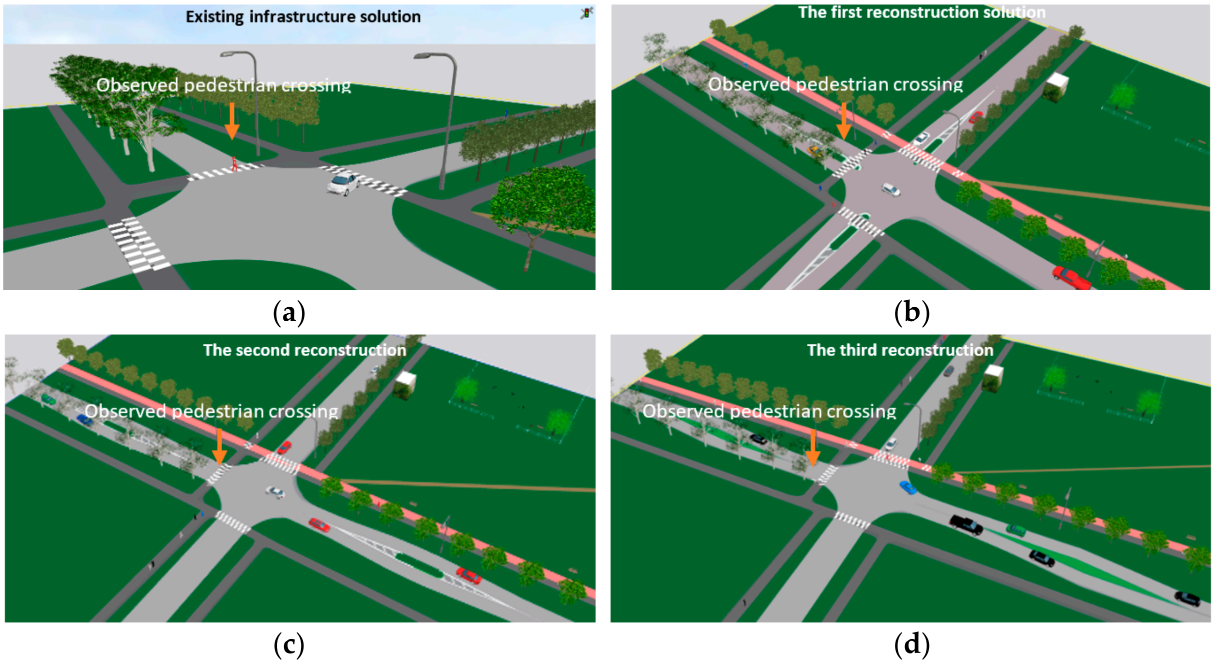


Figure 4. Traffic microsimulation model for the existing solution (**a**) and proposed reconstruction solutions (**b**–**d**).

In this case, selection of the optimal solution was based on the analyses of incoming speeds and traffic flow indicators.

The traffic flow indicators used to compare the reconstruction solution were the average QLen and maximum queue length QLenmax expressed in meters (m), the average vehicle delay VehDelay expressed in seconds per vehicle (s/veh), the number of vehicle stops at the STOP intersection (number), and the delay due to stopping VehDelaySTOP (s/veh). The results are presented in detail in [34]. Table 4 shows the results for the maximum $QLen_{max}$ queue length and the average VehDelay vehicle delays. By applying traffic microsimulations, a comparison of incoming speeds (km/h) on the main route was carried out for all infrastructure solutions and different traffic volumes (Table 5).

Table 4. Comparison of traffic flow indicators.

	Counted Traffic		Increase 100%		Increase 150%		Increase 200%	
	QLenmax	**VehDelay**	**QLenmax**	**VehDelay**	**QLenmax**	**VehDelay**	**QLenmax**	**VehDelay**
Existing Inters.	10.38	1.59	28.28	3.85	35.95	4.56	38.5	11.97
Solution 1	13.79	1.85	36.29	5.13	41.57	7.59	42.4	15.71
Solution 2	22.63	2.06	38.44	4.31	39.84	11.17	43.62	20.41
Solution 3	27.15	2.78	37.6	6.54	44.87	12.07	45.51	25.2

Table 5. Comparison of approaching speeds (km/h)—the main road.

		Counted Traffic	Increase 100%	Increase 150%	Increase 200%
Existing Intersec.	East	51.07	46.75	43.93	41.07
	West	50.15	45.43	43.55	40.67
Solution 1	East	38.95	35.15	32.65	29.80
	West	27.88	28.56	30.52	21.20
Solution 2	East	33.39	35.19	33.99	29.27
	West	26.95	29.03	26.94	28.85
Solution 3	East	38.5	36.1	33.66	30.49
	West	28.87	29.8	28.08	28.93

According to the presented results, reconstruction solution 1 has the best traffic flow indicators in most traffic scenarios (Table 4), and, together with reconstruction solution 2, it also has the best dynamic indicators, i.e., the largest reduction in incoming speeds (Table 5). The chosen solution for the reconstruction is a solution with pedestrian islands because in addition to reducing speeds, it narrows the conflict zone and divides it into two independent conflict zones, which allow pedestrian crossing to occur in stages. This has significant benefits for pedestrians, especially for children who, up to a certain degree of cognitive development, do not have the ability to properly assess the incoming speed of a vehicle, have a longer reaction time [28], and take longer to move through the conflict zone [36,37]. A narrowed pavement equates to a shorter stay in the conflict zone, which is particularly advantageous for pedestrians, especially for the older pedestrian population who have problems with mobility.

A comparison of the measured and modeled speed for the existing conflict zone for the eastern access lane was carried out and is shown in the cumulative diagram in Figure 5. The difference was less than 1% (0.8%), which showed that the model produced realistic results and did not need to be calibrated.

A detailed analysis and comparison of incoming vehicle speeds for the existing infrastructure solution of the conflict zone and the selected reconstruction solution (pedestrian island and narrowing of the conflict zone) will be carried out in future studies.

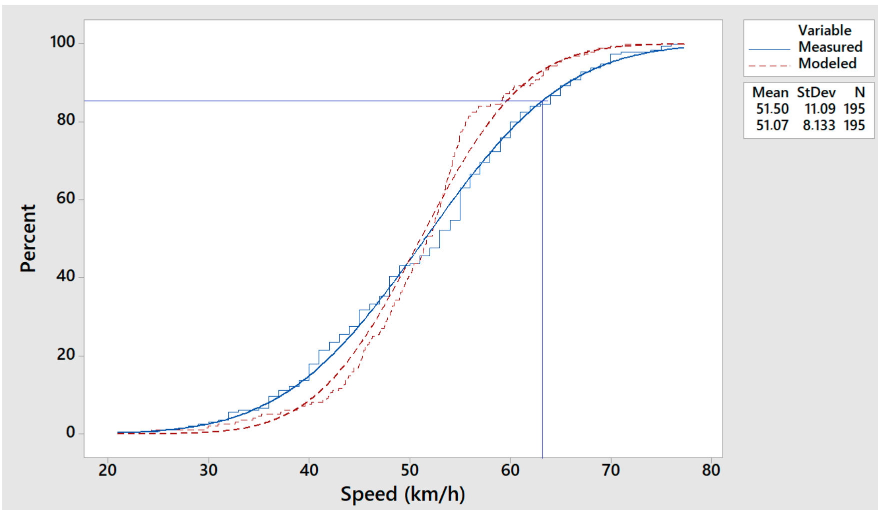


Figure 5. Cumulative measured and modeled speed diagram for an existing pedestrian crosswalk.

5. Results and Discussion

In this section, the results of the analyses of pedestrian and motorized traffic according to the methodology presented in Figure 1 are presented and discussed.

5.1. Statistical Analysis of the Database: Pedestrians

In Table 6, the results of the data analyses of pedestrian behavior are presented. The results for children and young people (up to 18 years of age) and adult pedestrians (over 18 years of age) were analyzed separately due to possible comparisons with earlier research results. Moreover, the influence of independent variables on the crossing and reaction times was analyzed in earlier research [28,36,37], and it was shown that the influence of the same independent variables on two different dependent variables was different. The data in Table 6 show the number of observed crossings (N), the mean of the dependent variables—crossing and reaction times in seconds—and the standard deviation, median, minimum, and maximum values of the datasets for the observed dependent variables. An analysis of the data distribution using the Anderson–Darling test was performed, and the null hypothesis was as follows: the data follow a normal distribution, with a significance threshold of 0.05.

Table 6. Basic statistical indicators of pedestrian behavior.

	N	Mean	StDev	Min	Max	Median	A–D	*p*
Child crossing time	89	4.53	0.67	2.96	6.78	4.53	0.701	0.065
Child reaction time	89	0.76	0.91	0.00	3.94	0.43	5.75	0.000
Adult crossing time	19	4.77	1.40	1.85	8.41	4.66	0.42	0.294
Adult reaction time	19	1.24	1.80	0.00	7.61	0.87	1.84	0.000

The results of the Anderson–Darling test showed that for the dependent variable crossing time, the null hypothesis could not be discarded, i.e., the data groups followed a normal distribution.

The results of this study (Table 6) show that children have faster reaction times and a lower standard deviation than adult pedestrians, which differs from the results of previous studies [28] in which children of younger ages had statistically significant longer reaction times than adults. The shorter reaction time of children can be explained by the fact that there was a significant number of elderly pedestrians in the group of adult pedestrians at the analyzed location. The results also show slightly shorter crossing times for children compared to adult pedestrians; we expected a more significant difference, but the results match previous research [36] because teenage children move more slowly through the conflict zone than younger children.

An analysis of the influence of independent variables (Table 2) on the dependent crossing time and reaction time variables was performed, and the results are shown in Table 7. Given that a large number of influential (independent) variables are categorical, the non-parametric Spearman Rho test was chosen for correlation analysis. Compared to the Pearson correlation coefficient, the Spearman correlation does not require continuous-level data. The Pearson coefficient assumes a linear relationship between the two variables, whereas the Spearman coefficient works with monotonic relationships as well [41,42]. Table 7 shows the results for the Spearman Rho correlation coefficient (SR) and *p*-value (*p*) for all data groups and both dependent variables.

Table 7. Comparative analysis of correlations using the Spearman Rho statistical test.

	Variables	Children and Teenagers				Adult Pedestrians			
		Crossing		Reaction		Crossing		Reaction	
		SR	*p*	SR	*p*	SR	*p*	SR	*p*
1.	Age group	0.63	**0.02**	−0.51	**0.04**	0.48	**0.03**	0.63	**0.02**
2.	Gender	0.05	0.63	0.02	0.89	−0.52	**0.03**	0.48	**0.05**
3.	Supervision	*	*	*	*	*	*	*	*
4.	Special need	*	*	*	*	0.49	**0.04**	0.35	0.09

Table 7. *Cont.*

	Variables	Children and Teenagers				Adult Pedestrians			
		Crossing		Reaction		Crossing		Reaction	
		SR	*p*	SR	*p*	SR	*p*	SR	*p*
5.	Group number	−0.52	**0.04**	−0.17	0.12	0.47	**0.04**	−0.39	0.10
6.	Talking on mobile/listening to music	*	*	*	*	*	*	*	*
7.	Mobile SMS/Internet	0.11	0.29	0.61	**0.02**	*	*	*	*
8.	Crossing outside crossing	−0.05	0.62	0.10	0.37	−0.39	0.11	0.05	0.83
9.	Running	−0.61	**0.02**	0.45	**0.05**	*	*	*	*
10.	Checking left	0.50	**0.01**	0.82	**0.00**	0.06	0.81	0.89	**0.00**
11.	Checking right	0.48	**0.01**	0.78	**0.00**	−0.06	0.81	0.86	**0.00**
12.	Veh arrives left	−0.03	0.76	−0.01	0.90	0.02	0.90	−0.33	0.15
13.	Veh arrives right	−0.48	**0.00**	−0.01	0.90	0.07	0.75	−0.19	0.42
14.	Veh stopping left	0.55	**0.00**	0.06	0.60	0.00	1.00	0.39	0.15
15.	Veh stopping right	0.47	**0.00**	0.06	0.59	−0.01	0.90	0.11	0.65
16.	Veh breaking left	0.01	0.93	0.04	0.72	0.00	1.00	0.34	0.15
17.	Veh breaking right	0.45	**0.00**	0.03	0.77	0.08	0.75	0.19	0.42
18.	Total number of children at ped crosswalk	−0.33	**0.01**	−0.39	**0.01**	0.11	0.67	−0.63	**0.04**
19.	Total number of pedestrians at ped crosswalk	−0.88	**0.00**	−0.12	0.25	0.68	**0.04**	−0.59	**0.04**
20.	Number of cyclists at ped crosswalk	0.09	0.38	0.07	0.55	*	*	*	*

* All values in the database are identical.

In Table 7, statistically significant parameters are presented in bold. The age group of both children and adults affected both the crossing and reaction times, which is in line with previous research [28,36,42]. Adult gender, according to the results of this analysis, affected both crossing and reaction times, and previous studies have produced different results in the case of gender [36,42,43]. For adults, motor disorders were shown to affect the crossing time, which was expected. The number of group members also affected the crossing time, which is in line with previous studies [36,37,42], but this study did not show an effect on reaction time, which does not coincide with existing research [28]. Children's running was negatively correlated with crossing times and positively correlated with the reaction times of children, which is in accordance with previous research [36,37,42]. Checking the traffic situation (which means checking the arrival of the vehicle) was positively correlated with child crossing and reaction times and adult reaction times. Approaching and stopping vehicles were positively correlated with the crossing time of children, which was expected, but did not have an impact on the crossing time of adults, which was expected since the adult pedestrian group included a certain number of elderly pedestrians who could not walk faster. The total number of children at the pedestrian crosswalk extended both their crossing and reaction times but shortened the reaction time of adults. The total number of pedestrians increased the crossing time of children but shortened the crossing and reaction times of adult pedestrians. The analysis results of the influence of input parameters on the observed dependent variables—crossing and reaction times—of this database are comparable to existing research, but, because the amount of data was limited and only one location was examined, the conclusions of this analysis should be taken as preliminary and constrained to specific site conditions.

5.2. Statistical Analysis of the Database of Incoming Vehicle Speeds Obtained via Microsimulation

A detailed analysis of the incoming speeds of the eastern driveway in one-minute intervals during the peak hour and for ten different traffic scenarios was carried out for the existing solution of the conflict zone and the selected solution of reconstruction (presented in Figure 3).

Table 8 shows the descriptive statistics of the database for the existing traffic solution of the pedestrian crosswalk and Table 9 shows the statistics of the proposed reconstruction solution for all analyzed traffic volumes. For smaller traffic volumes, there were one-minute intervals in which there were no vehicles (Tables 8 and 9), and, with respect to the highest traffic volume in the reconstructed conflict zone, one-minute intervals occurred in which vehicles stood in a queue, and the speed was 0 km/h (Table 9).

Table 8. Basic speed statistical indicators—existing solution.

	N	Mean	StDev	Min	Max	Median	Variance	A–D	*p*
Counted traffic	559	51.07	7.53	12.5	59.87	53.42	56.63	44.7	0.000
Increase 50%	591	49.18	7.51	14.9	60.07	51.92	56.27	24.1	0.000
Increase 100%	599	46.75	8.38	12.4	58.30	49.07	70.14	18.5	0.000
Increase 150%	600	43.93	8.72	14.48	57.79	45.83	76.07	8.9	0.000
Increase 200%	600	41.07	9.31	13.4	57.29	42.22	86.61	4.7	0.000
Increase 250%	600	38.02	9.77	10.64	57.02	39.30	95.53	3.7	0.000

Table 9. Basic speed statistical indicators—reconstruction solution.

	N	Mean	StDev	Min	Max	Median	Variance	A–D	*p*
Counted traffic	562	38.95	6.00	7.9	59.08	40.85	36.00	46.7	0.000
Increase 50%	592	36.93	6.85	7.7	48.12	39.81	46.88	30.0	0.000
Increase 100%	600	35.15	6.94	7.8	48.87	36.77	48.19	17.2	0.000
Increase 150%	600	32.65	7.61	8.9	45.45	34.30	57.84	9.6	0.000
Increase 200%	600	29.80	7.87	7.6	43.72	30.43	61.99	3.0	0.000
Increase 250%	598	26.17	8.05	5.6	42.87	26.52	64.79	1.2	0.000

An analysis of the distribution of data using the Anderson–Darling test was performed and the null hypothesis was as follows: the data follow a normal distribution, with a significance threshold of 0.05. The results are shown in Tables 8 and 9. The analysis of the distribution of data was carried out to select a statistical test for the evaluation of statistically significant differences between individual datasets.

A normalized cumulative speed diagram is shown for the existing infrastructure solution in Figure 6 and the reconstructed one in Figure 7. In both diagrams, the operating speed of V85 was marked, and the reduction in operational speed for the reconstructed conflict zone could be clearly observed, which was expected. There was a noticeable reduction in operating speeds with respect to the increased traffic volume for both infrastructure solutions.

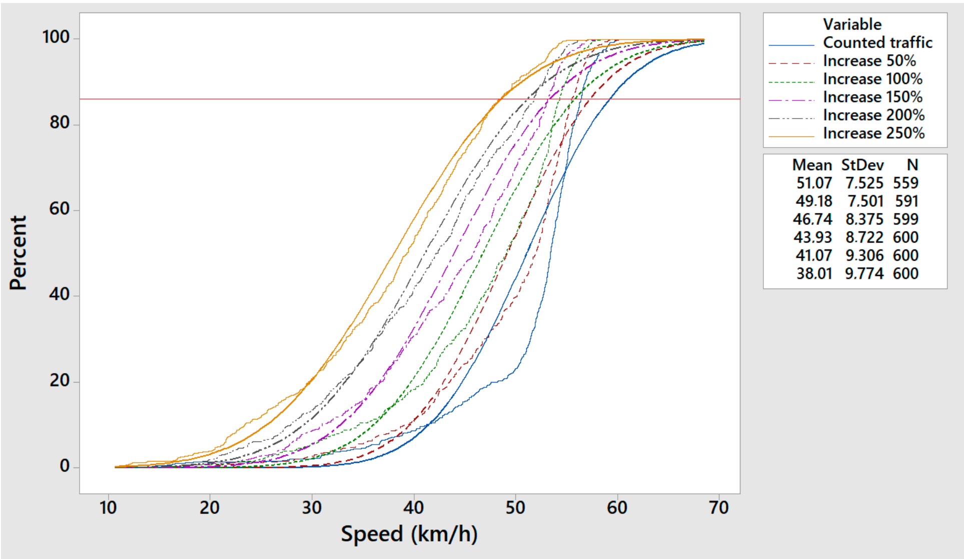


Figure 6. Cumulative speed diagram for an existing pedestrian crosswalk (normalized).

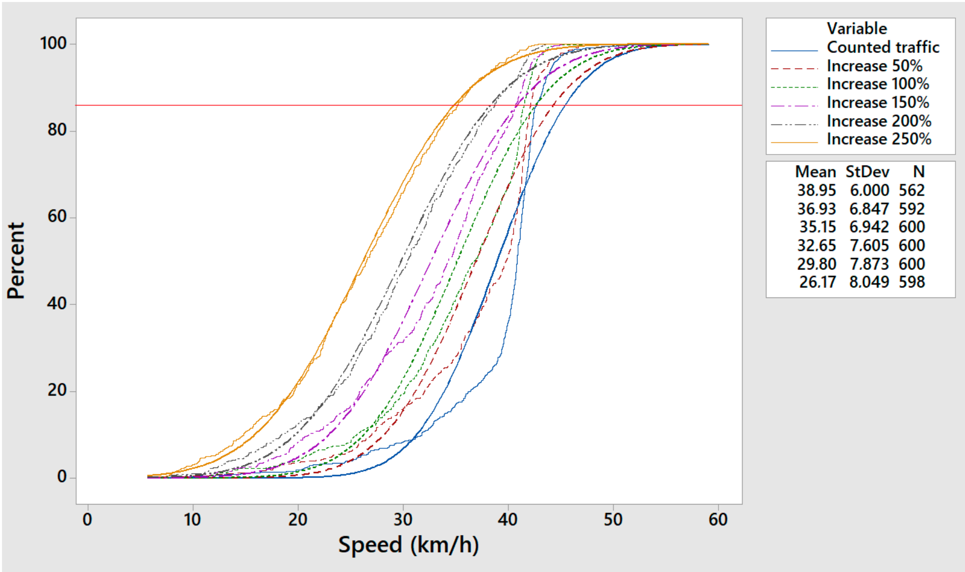


Figure 7. Cumulative speed diagram for a reconstructed pedestrian crosswalk (normalized).

With the increase in traffic volume, the operating speed (V85) decreased and the mean and median speed (expected) and standard deviation increased. This shows that traffic flows were still not completely forced at all one-minute intervals, but a combination was observed; thus, because the vehicles periodically drove at the desired speed, the maximum speed decreased, which was also expected. The minimum speed varied due to the impact of pedestrian flow and did not exhibit sensitivity to the increase in traffic volume within the analyzed data, which was also expected.

5.2.1. Analysis of the Impact of Traffic Volume Increases on Traffic Conditions and Incoming Vehicle Speeds

According to the results of the Anderson–Darling test, the null hypothesis for all datasets could be rejected, and it could be concluded that none of the datasets of the modeled velocities followed normal distributions. Thus, nonparametric Bonett and Levene tests were used to evaluate the statistically significant differences between the datasets [36]. The null hypothesis was as follows: the datasets statistically do not differ significantly, and the set significance threshold is 0.05. The analysis results of the increase in traffic volume with respect to the incoming vehicle speeds for the existing (Table 10) and reconstructed (Table 11) conflict zones are presented.

Table 10 presents the results of the analysis between the counted traffic instances and the increase in traffic in order to determine the degree of traffic increase needed for a statistically significant reduction in incoming speeds. For the existing pedestrian crosswalk and the counted traffic volume, a statistically significant difference in incoming speeds was achieved for an increase in traffic volume of 150% according to the results of both tests and the result of the Levene test for a traffic volume increase of 100%. In the continuation of the analysis, a comparison of adjacent data groups was carried out to determine when the homogenization of speeds occurred due to the traffic volume. For traffic volumes that increased by 150% or more, traffic slowed down, and there was no statistically significant difference in speeds in the datasets, as observed in Table 10.

The reconstructed pedestrian crosswalk showed greater sensitivity to the increase in traffic volume; thus, according to the results of the Levene test, the speed statistically significantly differed with an increase in traffic volume of 50% and, according to the results of both tests, with a 100% increase. The reconstructed conflict zone also did not have a statistically significant difference with respect to speed when traffic increased by 150% or more, as observed in Table 11.

Table 10. Impact of traffic volume on incoming vehicle speeds for the existing pedestrian crosswalk.

	Counted/ Incr. 50%	Counted/ Incr. 100	Count/ Incr. 150	Incr. 50/ Incr. 100	Incr. 100/ Incr. 150	Incr. 150/ Incr. 200	Incr. 200/ Incr. 250
σ1/σ2	1.00	0.90	0.86	0.90	0.96	0.94	0.95
V1/V2	1.01	0.81	0.74	0.80	0.92	0.88	0.91
Bonett	- *	- *	- *	- *	- *	2.77	1.72
p	0.97	0.13	0.02	0.06	0.40	0.10	0.19
Levene	6.2	25.6	52.8	7.52	4.52	3.05	0.61
p	0.13	0.00	0.00	0.01	0.03	0.08	0.44

* In all cases where there was a difference in the number of data, the values of the Bonett test were not obtained, but the significance of the data was calculated.

Table 11. Impact of traffic volume on incoming vehicle speeds for a reconstructed pedestrian crosswalk.

	Counted/ Incr. 50%	Counted/ Incr. 100	Count/ Incr. 150	Incr. 50/ Incr. 100	Incr. 100/ Incr. 150	Incr. 150/ Incr. 200	Incr. 200/ Incr. 250
σ1/σ2	0.88	0.86	0.79	0.99	0.91	0.96	0.98
V1/V2	0.77	0.75	0.62	0.97	0.83	0.93	0.96
Bonett	- *	- *	- *	- *	3.76	0.76	-
p	0.07	0.03	0.00	0.81	0.05	0.38	0.55
Levene	18.92	39.7	73.10	2.27	6.37	0.90	0.79
p	0.00	0.00	0.00	0.13	0.01	0.34	0.37

* In all cases where there was a difference in the number of data, the values of the Bonett test were not obtained, but the significance of the data was calculated.

The results presented in Tables 10 and 11 show that the impact of an increase in traffic volume on incoming vehicle speeds was sensitive to the infrastructural solution of the observed vehicle–pedestrian conflict zone. The reconstructed conflict zone, which slowed down incoming speeds, showed greater sensitivity to increasing vehicle traffic volume.

The expected increase in traffic volume certainly had a negative impact on traffic flow indicators—longer queues and higher average vehicle delays. The average vehicle delay indicators in conditions of a 100% increase in traffic volume were close to 4 s/veh for the existing conflict zone and 5 s/veh for the reconstructed one (Table 4). When the traffic volume was increased by 150%, the mean vehicle delays were 5 s/veh and 8 s/veh, respectively (Table 4), which were still acceptable values because average delays per vehicle that are less than 10 s are considered service level A. The average delay values should be viewed in relation to the position of the observed pedestrian crossing, which is located in a residential part of the traffic network in which safety parameters are maximized and flow parameters are optimized.

5.2.2. Analysis of the Impact of Reconstruction on Incoming Vehicle Speeds

An analysis of the impact of conflict zone reconstruction for all levels of traffic volume was carried out and is presented in Table 12, and the basic characteristics of the compared data groups were also examined: mean speeds in km/h (Vmean), standard deviations (σ), variances (Varian), and results of statistical tests for the existing (Exist) and reconstructed (Recon) conflict zone.

In accordance with data distribution results (Tables 8 and 9), Bonett and Levene nonparametric tests were used, similar to previous analyses. The null hypothesis was as follows: the datasets do not differ statistically significantly, and the set significance threshold is 0.05.

Table 12. Analysis of the impact of reconstruction on incoming vehicle speeds.

	Counted		Increase of 50%		Increase of 100%		Increase of 150%		Increase of 200%		Increase of 250%	
	Exist	**Recon**	**Exist**	**Recon**	**Exist**	**Recon**	**Exist**	**Recon**	**Exist**	**Recon**	**Exist**	**Recon**
V_{mean}	51.07	38.95	49.18	36.93	46.75	35.15	43.93	32.65	41.07	29.80	38.02	26.17
σ	7.33	6.00	7.51	6.85	8.38	6.94	8.72	7.61	9.31	7.87	9.77	8.05
Varian	56.63	36.00	56.27	46.88	70.14	48.19	76.07	57.84	86.61	6.99	95.53	64.79
Bonett	- *		- *		- *		10.74		19.24		- *	
p	0.014		0.054		0.001		0.001		0.000		0.000	
Levene	7.95		9.35		10.42		11.27		19.10		17.93	
p	0.005		0.003		0.001		0.001		0.000		0.000	

* In all cases where there was a difference in the number of data, the values of the Bonett test were not obtained, but the significance of the data was calculated.

The average speed results of all traffic scenarios and traffic volumes for existing and reconstructed conflict zones are shown in Figure 8.

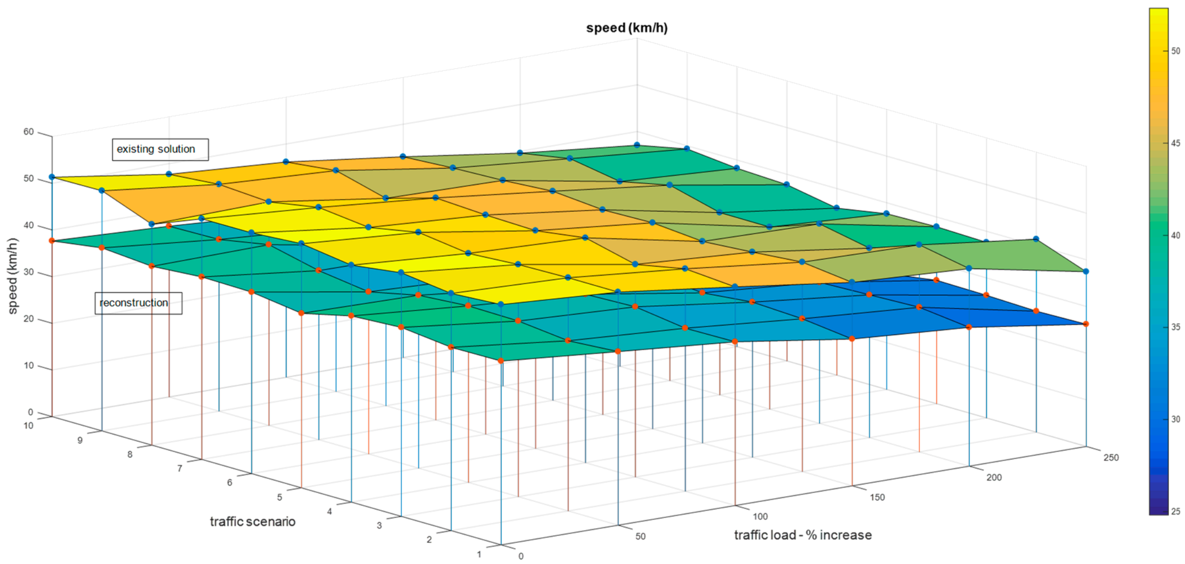


Figure 8. Average speeds for all traffic volumes and vehicle encounter scenarios for an existing and reconstructed pedestrian crosswalk.

For all traffic volume levels, the reconstruction of the conflict zone statistically significantly slowed down incoming vehicle speeds. This was the expected confirmation of successful reconstruction in the observed case study, which aimed to increase the safety of pedestrian flows, especially the pedestrian flow of vulnerable transport users, such as children, young people, and elderly pedestrians.

6. Conclusions

The planning and design of transport infrastructure should take into account the local specificities of users and traffic infrastructure, as well as any expected changes in traffic conditions. Within this research study, an analysis method for a critical traffic infrastructure segment with detected traffic safety issues was developed and applied. Based on the on-site measurements of pedestrian and motorized traffic indicators and an analysis of the impact of infrastructural solutions using the traffic microsimulation method, the optimal solution was selected.

The conducted case study enabled detailed analyses of two groups of pedestrians—young and elderly. The results of the pedestrian behavioral analysis showed that children have a faster reaction time than adult pedestrians, which differs from previous results [28,36], and higher walking speeds through the conflict zone, which also disagrees with the results of previous studies [36,43]. These findings were obtained because elderly people comprised the majority of the adult pedestrian population. Both groups of pedestrians, children and adults, showed a statistically significant influence of age on reaction time, comparable to those reported in [23,24,28], and crossing speed, which agrees with the results of most studies conducted [22,23,25,43]. For adult pedestrians, the pedestrians' gender was also a statistically significant parameter for both reaction times and crossing speeds [25], but this was not the case for children, which coincides with the results of previous studies carried out on signalized crosswalks within the same urban network [36,43]. The impact of children's gender happens to be locally dependent as, in some analyses, the influence of children's gender was not a statistically significant variable and, in others, it proved to be significant [44]. For adults, problems with mobility were shown to affect crossing times, which was expected. Both groups showed statistically significant sensitivity relative to the total number of pedestrian-on-pedestrian crosswalks, and, with respect to crossing speeds, both groups exhibited sensitivity to movement in the group, which agrees with previous research findings [36,43].

The analysis of risky behaviors at the observed location showed that running was a statistically significant variable for children, while adult subjects did not run across the road. The analysis results of the behavior of adult pedestrians showed that they did not interact with the incoming vehicles' flow, nor check the traffic situation, and both the approach of the vehicle and braking had an impact on their crossing speed. All these variables had a statistically significant impact on children. These results indicate that the heterogeneous flow of pedestrians complicates interactions with vehicle flow, which may prove to be extremely important for the safety of older pedestrians in increasing traffic volume conditions, as expected at the observed location.

The results of the analysis of the selected location showed that the selected reconstruction solution exhibited a statistically significant decrease for all traffic volume levels, which is the expected goal of spatial interventions.

The results of traffic microsimulations showed that an increase in traffic volume resulted in a statistically significant reduction in speed only for increases in traffic of 150% (existing conflict zone) and 100% (reconstructed), which is not a sufficiently reliable measure of increasing traffic safety, especially if the results show that the increase in traffic volume has no impact on the behavior of older pedestrians. This phenomenon should be investigated more in future research.

The reconstructed conflict zone was more sensitive to increases in traffic volume (for a smaller increase in traffic, a statistically significant decrease in the incoming flow of vehicles was observed). It follows that there is a connection between the infrastructure solution, the increase in traffic, and the decrease in incoming speeds [45,46].

The methodology used in this study—the collection of motor and pedestrian traffic data at the actual location, analyses of influencing parameters on pedestrian behavior, and microsimulation traffic model development of the reconstruction zone with the aim of improving traffic safety under conditions of increasing traffic volume—enabled the interrelation analysis of all traffic users at the selected location. The planned reconstruction resulted in a decrease in traffic with respect to existing and increased traffic volume conditions.

However, it was shown that child and adult (in this case, those who were older) pedestrians are not affected by incoming traffic flows in the same manner. Children show greater sensitivity to incoming traffic than older pedestrians, which can put older pedestrians at greater risk in locations where higher traffic volumes are expected; this is confirmed by data on the number of elderly pedestrians killed in Croatia. This conclusion also raises the question of whether only the general impact on vehicle speed should be analyzed when analyzing the effectiveness of traffic-calming measures, such as the one implemented in this study. In cases where it is determined that the location is regularly used by older pedestrians, whether the offered solutions are adequate should also be analyzed in relation to the safety of older pedestrians.

Limitations and Further Research

The aim of the presented research was to develop a methodology for an individual conflict zone, which is why it was not possible to analyze all parameters of pedestrian behavior determined to be important in previous research. For the modeling of pedestrian behavior in the conflict zones of non-signalized crosswalks, it is therefore necessary to conduct research at different locations in order to form a relevant database.

Solution comparisons for improving the traffic safety of conflict zones were based on analyses of speed as an indicator of safety, and the analysis of the selected output parameters of the VISSIM model was based on the indicators of traffic flow. The limitation of this approach is that only these two main criteria were used to select the solution. For future research, we recommend introducing additional criteria (environmental, economic, user preferences, etc.) via the application of multi-criteria optimization analyses.

By applying expert systems and neural networks, the plan is to develop prediction models for the behavior of pedestrians in a conflict zone, which will be useful tools in selecting optimal measures to increase traffic safety for special groups of vulnerable users.

The VISSIM microsimulation model proved to be a good tool for the analysis of traffic safety parameters [32,33]. Based on the results analysis of the traffic participant trajectories of the VISSIM traffic microsimulation model, future research will focus on the modeling of potential vehicle–pedestrian conflicts by including it in the proposed methodology.

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