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Research Article

A Novel Integrated Model under Fuzzy Environments as Support for Determining the Behavior of Pedestrians at Unsignalized Pedestrian Crossings

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Pedestrians as a vulnerable category of traffic participants demand a special attention, particularly regarding their behavior at unsignalized pedestrian crossings. Unquestionably, when crossing a road at these types of pedestrian crossings, there is a potential risk, for both the pedestrians and other traffic participants, as well. Accordingly, this article shows the research on pedestrians' behavior at unsignalized intersections, conducted at four locations in the urban environment of Novi Sad. The main goals of this study are reflected in developing a multiphase model by integrating different approaches into one original unique model. First, the efficiency of the observed locations of pedestrian crossings was determined by applying a model consisting of DEA (Data Envelopment Analysis), fuzzy DEA, entropy, CRITIC (CRiteria Importance Through Intercriteria Correlation), fuzzy FUCOM (Full Consistency Method), fuzzy PIPRECIA (PIvot Pairwise RElative Import Criteria Assessment), and fuzzy MARCOS (Measurement of alternatives and ranking according to COmpromise solution). Then, the following aim of this study is to determine the values of the critical interval and then to compare these values with the accepted interval, which can be considered one of the criteria of safe pedestrians' crossing the roadway. Apart from this, the aim is related to determining the characteristics of pedestrians' behavior at unsignalized crossings, with a special reference to gender differences, as well to the fact whether the pedestrian crosses the roadway as an individual or within a group. After the empirical research and data classification, efficiency calculation, an extensive statistical and verification analysis was conducted to determine the set goals. The results imply that the relationship of the values of the accepted and critical intervals indicates the occurrence of the risky behavior of a certain number of pedestrians, which is reflected in accepting the intervals that are not completely safe for crossing the roadway and which can negatively affect the sustainable functioning of the traffic system.

1. Introduction

Behavior of pedestrians and drivers at pedestrian crossings directly affects the level of service of pedestrian flows, since the pedestrian waiting for an appropriate gap causes delays, which are the basic parameter for determining the level of service of pedestrian flows [1, 2]. Simultaneously, pedestrian flows can also affect vehicles' delays at unsignalized intersections [3]. Pedestrians crossing the roadway depend on numerous factors that affect their decision and the way of crossing the roadway (age and gender of pedestrians, drivers' behavior, vehicles' characteristics, road geometry, built environment of streets, construction measures, etc.) [4]. Researchers found evidence that women were more inclined than men to use the crossing [5]. Taking into account the different needs of users, the goal is to provide infrastructural facilities and elements that are planned and designed according to the security principles and that correspond to the projected speed and road function as well as safe infrastructure for different groups of pedestrians, such as children, the elderly, and persons with disabilities [6]. From the traffic safety aspect, for example, it was concluded that the construction of a raised pedestrian crosswalk had a positive effect on the pedestrian traffic conditions. This improvement is reflected in the reduction of pedestrian delays and in an increase in the level of service offered to pedestrians [7]. At the pedestrian crossings with the refuge island, it was proved that pedestrians accept shorter time intervals between vehicles for road crossing when they have previously gone across the road part to the refuge island. Factors such as road width, number of traffic lanes, and allowed speed affect pedestrian crossing behavior and have an impact on pedestrian-vehicle conflicts [8].

For every pedestrian crossing, the value of the critical interval can be determined, that is, the minimum necessary time for pedestrians to safely cross the roadway at a certain speed of movement. When pedestrians are in front of a pedestrian crossing, they estimate by assessing the traffic situation whether the available time interval to the vehicle's arrival at the pedestrian crossing is sufficient for them to cross the roadway safely and they make a decision "yes" or "no"; that is, they decide whether to accept or refuse the offered interval. Thus, a pedestrian assesses each interval for the specific traffic situation and accepts those intervals for which they assess to be longer than the critical ones; that is, that they are sufficient for safe crossing the road. The accepted and the refused intervals by the pedestrians form a unique set of conditions that can be used in the statistical analysis, which will be shown in this article.

In the region of Southeastern Europe, there have not been any significant research studies on the behavior of pedestrians when crossing the roadway; therefore, there have not been any analyses of the acceptable intervals. Generally, the research studies in this field both in Europe and in the world are sparse, in relation to some other parameters of the traffic flow, which have been more analysed (flow, velocity and the density of traffic flow, critical gaps and headway, travel time, etc.). Since pedestrians represent an integral part of the sustainable traffic system of a city, it is extremely important to know the patterns in which these categories of participants behave in local traffic conditions so as to enable city's traffic and urban development towards a sustainable direction.

The aim of the research conducted for the needs of this article was to determine the value of the acceptable intervals at several locations of the unsignalized pedestrian crossings, different in their geometrical characteristics and traffic conditions. Comparative analysis of the acceptable and critical interval was used for creating the model of pedestrians' behavior depending on the characteristics of the location of the unsignalized pedestrian crossing. In addition, the aim was to determine the influence of different factors on the behavior of pedestrians when crossing the roadway in the conditions of local traffic, as well as to conduct the comparative analysis of the obtained results of the research studies conducted in the world at unsignalized pedestrian crossings. Namely, the results of the research studies conducted in the world imply that the factors such as gender and the number of pedestrians in a group when crossing the roadway affect the values of the acceptable pedestrian intervals. Considering the fact that traffic conditions, regulations, and habits, as well as traffic culture, are usually different around the world, the results of the research conducted on the territory of Europe [4, 9, 10] are completely different from those conducted, for example, in Asia [11–13]. The research studies conducted in Europe show that women choose shorter intervals in comparison with men and that pedestrians circulating in groups choose longer intervals for crossing. Additionally, the aim and contribution of this article are reflected in forming an original integrated MDCM model for determining criterion weights, which involves a combination of two objective methods in a crisp form and two subjective methods in a fuzzy form. Integration of subjective-objective methods was made in order to achieve more accurate and approximately optimal results from criterion weights aspect. Such integration should ensure precise answers to various questions and give potential approximately optimal solutions in various fields taking into account different constraints. After defuzzification, their values were averaged using the Bonferroni aggregator, which gives additional significance to this model. Previously, the DEA and fuzzy DEA methods were applied to determine the efficiency of the observed pedestrian crossings, and the final efficiency was determined using the fuzzy MARCOS method. The model that takes into account the combination of objectivity, subjectivity, and fuzzy theory can be applied in other fields as well.

In addition to the introductory notes on the cause and the aims of the research, there is also an overview of the basic terms related to the characteristics of pedestrians' behavior at the pedestrian crossing, as well as a short retrospective of previous research studies conducted in this field. The method and procedure of the conducted research at four locations of the pedestrian crossings were described, after which the most important results were shown. The comparative analysis of pedestrian intervals (gaps) was performed and the comparison with the values of the critical interval for each location. Then, the intervals were analysed depending on the fact whether the pedestrian crosses the roadway alone or in a group. After the discussion of the achieved results and the comparison with similar research studies conducted in the world, the conclusion as well as the directions on further research studies in this field was given. The obtained results can be used for a detailed analysis of the microlocation of the pedestrian crossing and the formation of a plan of possible infrastructural and regulatory interventions at the location of the pedestrian crossing, in order to raise the level of pedestrian safety and increase the level of service.

2. Short Overview—Characteristics of the Behaviour of Pedestrians at the Pedestrian Crossing

The process of pedestrians' crossing the roadway is defined on the basis of subjective, that is, individual characteristics of the pedestrian, which interact with objective factors (location, traffic density, vehicles velocity, and vehicular follow-up gap). When analysing the behavior of the pedestrian and the drivers approaching the pedestrian crossing in the vehicle, a special attention is directed to the following characteristics:

(i) Demographic characteristics of the participants (gender, age)
(ii) Pedestrian delay gap—the time interval for waiting/making decision for crossing
(iii) Velocity of the pedestrian and the vehicle
(iv) Category and position of the vehicle in relation to the pedestrian
(v) Risky behavior of pedestrians when crossing the roadway.

The process of pedestrians crossing the roadway in case the interval is accepted consists of the following procedures:

(i) Arrival of the passengers at the place where they want to cross the roadway
(ii) Process of waiting for the adequate interval for crossing
(iii) Process of crossing the roadway
(iv) Stepping on the opposite edge of the roadway.

In order to present the basic characteristics of the accepted intervals, it is necessary to understand the terms and make distinction among several types of intervals found in the literature [14, 15]. There are intervals that are defined in relation to the location characteristics (adequate and critical intervals), as well as the intervals that depend on the conditions that are relevant at the moment when a pedestrian is trying to cross the roadway at the pedestrian crossing (available, accepted, and rejected interval).

The available interval is the time interval that is available to the pedestrian and represents the current time distance between the pedestrian stepping onto the roadway and the approaching vehicle. This time interval is used as a comparative criterion for pedestrian's decision whether to accept the interval or not. If the pedestrian accepts the available interval, that is, if they cross the roadway within that interval, then it becomes the accepted interval. Otherwise, the available interval becomes the rejected interval. Adequate interval or critical interval for every location is determined when the distance the pedestrian has to cover is divided by the pedestrian's velocity, and the adequate starting time is added to that value. However, it should be emphasized that in this calculation, the approximate velocity of pedestrian circulation is used, while the real velocity of each pedestrian differs, which actually depends mostly on age and physical abilities, alongside other conditions occurring at the observed location. Comparison of the values of the accepted and critical interval is used as one of the criteria for determining the term of safe pedestrian crossing the roadway [16].

Pedestrian delay, as one of the parameters occurring in research studies, implies that with the increase in the delay, the pedestrians become impatient and they accept shorter intervals for crossing the roadway [17]. The same authors reached a conclusion that the probability of accepting the smaller interval increases with the number of missed opportunities for crossing. Similar results have been found in other research studies [18, 19]. Observing the individual characteristics of pedestrians, such as gender, it was established in the research studies that women have greater delays than men; that is, they wait longer for the adequate crossing interval [20, 21]. Accordingly, the research studies have shown that women spend 27% of time longer waiting at the pedestrian crossing [11], while the crossing velocity is higher with men than with women [22, 23]. The research studies conducted on the territory of Asia show that pedestrians circulating in groups choose shorter gaps, consequently their behaviour is more aggressive, and the process of roadway crossing is more risky. The authors explain this result with the fact that pedestrians feel more protected within a group, and for that reason, they act more aggressively [24, 25]. Considering the fact that traffic conditions, regulations, and habits, as well as traffic culture, are completely different, the results of the research conducted on the territory of Europe are completely different from those conducted in Asia. Namely, the authors Yanis et al. [9] reached a conclusion that pedestrians within a group choose longer intervals for crossing the roadway in relation to those who do that individually. The pedestrian age is one of the most influential variables in the risk-taking behaviour at crosswalks [26, 27]. The findings of the generic model concluded that with the increase in the pedestrian age, there is a significant decrease in the probability of road crossing and it further decreases with the increase in the number of vehicle lanes [28].

The pedestrian behaviour, as well as an analysis of the dynamics between pedestrians and vehicles at unsignalized intersections, is usually a great source of data for mathematical modelling. Statistical analysis of the parameters, which affect the process of accepting a certain interval for crossing, enables the formation of mathematical models used for assessing the probability of the accepted pedestrian intervals. Logistic curve (logit) is usually used for the assessment of the accepted and rejected intervals, and it actually represents the probability of accepting the interval of a certain length. In this way, the acceptable pedestrian interval can be determined for a certain percentage of the population [9, 10, 29]. In accordance with modern technology and the development of traffic systems, there is a need to explore the relation between personal characteristics of pedestrians and their crossing behaviour in front of an automated vehicle (AV). The results of generalized linear mixed models showed that besides the distance from the approaching vehicle and existence of a zebra crossing, pedestrians' crossing decisions are significantly affected by the participants' age, familiarity with AVs, the communication between the AV and the pedestrian, and whether the approaching vehicle is an AV [30]. In another study, the game theory is used to analyse the interactions between pedestrians and autonomous vehicles, with a focus on yielding at crosswalks. Because autonomous vehicles will be risk-averse, the model suggests that pedestrians will be able to behave with impunity, and autonomous vehicles may facilitate a shift toward pedestrian-oriented urban neighborhoods [31]. The review of used literature and their contributions are summarized in Table 1 [9–11, 14–31].

As previously mentioned, local traffic conditions, different law enforcement and traffic culture, can lead to different patterns of pedestrian behaviour. Therefore, it is important to investigate the behaviour of pedestrians in local traffic conditions, because the obtained parameters enable the formation of a model that is based on variables that are the result of local measurements. In that way, the influences and specific qualities of the local environment would be valued, which was not the case on research locations of the study presented in this article. That would contribute to a more precise determination of the level of service at pedestrian crossings and future infrastructural and regulatory interventions on the street network.

MCDM methodology as part of operation research is very often applied for solving different problems in various fields. It is a very important and powerful tool for decision-making in traffic end transport engineering. Regardless of the fact that these are young methods that have been exploited for only a few years (fuzzy FUCOM, fuzzy PIPRECIA, fuzzy MARCOS), their applicability is at an enviable level. Apart from them, using entropy, CRITIC, and DEA methods mentioned previously represents a very comprehensive methodology for solving questions of efficiency. Table 2 shows a short review of the application of the MCDM method used in this study [32–43].

3. The Research Methods and Procedure

The flow chart of the conducted research study is shown in Figure 1 presented in the appendix. The overall flow of the research and the proposed methodology consists of 4 extensive phases and 14 steps with a larger number of activities at the lowest hierarchical level.

3.1. The First Phase. The first phase of research includes defining influential factors and data collection. It consists of four steps. The first step refers to recognizing the needs for research through a literature review and previous experience of the authors and knowledge of gap in the field that can be fulfilled by this research study. The second step of the first phase involves defining the influential factors related to the locations where the research was conducted. In the third step, the parameters of the model were defined: five inputs and two outputs in order to determine the efficiency of the observed locations. Inputs are the number of traffic lanes, vehicles' movement direction, length of pedestrian crossing, crossing time, and waiting time (Tables 3 and 4), while outputs are pedestrian flow and vehicle flow (Table 3). The vehicle flow is expressed in passenger car unit (PCU). It is common practice to consider the passenger car as the standard vehicle unit to convert the other vehicle classes. In the last, fourth step, the typical characteristics of pedestrians were defined in order to be able to form an adequate model of their behaviour. In order to collect relevant data, which would be used for forming a certain database, the research was conducted at four typical unsignalized pedestrian crossings in Novi Sad (Figure 2). The criterion for the selection was the number of traffic lanes and vehicles movement direction; thus, four types of locations were analysed: one traffic lane, one-way vehicles movement; two traffic lanes, two-way vehicles movement; two traffic lanes, one-way vehicles movement; and more than two traffic lanes, two-way vehicles movement.

The basic parameters necessary for the analysis are pedestrian delay, crossing velocity, and the lengths of the accepted and rejected intervals. All these mentioned parameters were obtained by local measurements with considering all specific features related to the behaviour of participants in typical situations. Data regarding all analysed parameters were collected by means of the method of the analysis of the video recordings made at the chosen locations. Measuring traffic flow parameters by processing videos is one of the oldest but also the safest methods that has been proven to be an efficient way of gathering data needed for analysis in a large number of researches so far. For that purpose, traffic flow of vehicles and pedestrians at the locations of the chosen unsignalized pedestrian crossings was taped. The recording was made in 18 March 2015 (Wednesday) during the period of morning peak hour (10 : 00–11 : 00). According to previous traffic research conducted on the territory of the city of Novi Sad, it has been determined that the morning peak hour is in the specified period, and it is recommended that all measurements be made in this interval, which is relevant for determining traffic flow parameters. For capturing traffic conditions for a typical weekday, it is recommended to collect field data on weekdays, such as Tuesday, Wednesday, and Thursday; and during months, such as September through November and/or February to April since these time periods represent more typical commute patterns. At this stage of the research, interviews were not conducted, because these kinds of data were not necessary for the model. The research was carried out in the real traffic conditions and can be repeated in the relevant periods. The recordings were then analysed in a certain software package used for video recording processing. The analysis of the video recording also enabled data collection regarding pedestrian delays. For the needs of the analysis, the following time sections were recorded:

t1: Pedestrian's arrival time to the pedestrian crossing

t2: The moment the pedestrian started the roadway crossing

Table 1: Review of the used literature and their contribution.

Reference	Objective of study	Contribution/Findings
HCM (2010)	Concepts, guidelines, and computational procedures for computing the capacity and quality of service of various highway facilities	Methodology of the level of service (LOS) for pedestrian flows at pedestrian crossings
MUTCD (2009)	Standards, guidance, options, and supporting information relating to the traffic control devices	Standardization of traffic control devices for pedestrian
Fitzpatrick et al. (2006)	Improving pedestrian safety at unsignalized crossings	Analysis of pedestrian intervals and determination of influential factors
Lobjois et al. (2013)	The effects of age and traffic density on street-crossing behaviour	With the increase in the delay, the pedestrians become impatient and they accept shorter intervals for crossing the roadway
Herrero-Fernández et al. (2016) and Nor et al. (2017)	Risky behaviour in young adult pedestrians/analysis of pedestrian gap acceptance and crossing decision	The probability of accepting the smaller interval increases with the number of missed opportunities for crossing
DiPietro and King (1970) and Hamed (2001)	Analysis of pedestrian gap acceptance/analysis of pedestrians' behaviour at pedestrian crossings	Women have greater delays than men at pedestrian crossings
Tiwari et al. (2007)	Pedestrian risk exposure at signalized intersections	Women spend 27% of time longer waiting at the pedestrian crossing
Rastogi et al. (2011) and Tarawneh (2001)	Study of pedestrian speeds at mid-block crossings/evaluation of pedestrian speed with the investigation of some contributing factors	The crossing velocity is higher with men than with women
Pawar and Patil (2015)/Wang et al. (2010)	Pedestrian temporal and spatial gap acceptance at mid-block street crossing/study of pedestrians' gap acceptance behaviour	Pedestrians circulating in groups choose shorter gaps, their behaviour is more aggressive, and the process of roadway crossing is more risky
Yanis et al. (2010)	Pedestrian gap acceptance for mid-block street crossing	Pedestrians within a group choose longer intervals for crossing the roadway
Lord et al. (2018) and Shaaban et al. (2018)	Perceptions of risk and crossing behaviours among the elderly/analysis of illegal pedestrian crossing behaviour	The pedestrian age is one of the most influential variables in the risk-taking behaviour at crosswalks
Kadali and Vedagiri (2020)	Role of number of traffic lanes on pedestrian gap acceptance and risk-taking behaviour at uncontrolled crosswalk locations	With the increase in the pedestrian age, there is a significant decrease in the probability of road crossing and it further decreases with the increase in the number of vehicle lanes
Papadimitriou et al. (2009)/Zhao et al. (2019)	Pedestrian behaviour models/gap acceptance probability model for pedestrians at unsignalized mid-block crosswalks based on logistic regression	Using the logistic curve (logit) for the assessment of the accepted and rejected intervals
Rad et al. (2020)	Pedestrians' road crossing behaviour in front of automated vehicles (AV)	Pedestrians' crossing decisions are significantly affected by the participants' age, familiarity with AVs, and the communication between the AV and the pedestrian
Millard-Ball (2018)	Analysis of the interactions between pedestrians and autonomous vehicles	Because autonomous vehicles will be risk-averse, the model suggests that pedestrians will be able to behave with impunity, and autonomous vehicles may facilitate a shift toward pedestrian-oriented urban neighbourhoods

t3: The moment the pedestrian finished the roadway crossing

t4: The headway of the approaching vehicle to the pedestrian crossing.

On the basis of the collected data, pedestrian delays occurred due to waiting at pedestrian crossings (t2-t1) and the time necessary for a pedestrian to cross the roadway (t3-t2) have been calculated , whereby the average pedestrian velocity was calculated, since the length of the pedestrian crossing was known for the given location. Critical interval for the location was determined by dividing the distance the pedestrian had to cover by the velocity of the pedestrian and then a certain starting time (3 s) is added to the value. The accepted intervals are obtained as the time difference between the moment when the passenger started crossing and the time headway of the vehicle approaching the pedestrian crossing. The rejected intervals are calculated as the time difference between two follow-up vehicles through the pedestrian crossing, in cases while the pedestrian was standing at the edge of the roadway and waited for the adequate interval for crossing.

The rejected intervals lower than 1 s are by previous research study recommendations excluded from the analysis, due to the assumption that these intervals are not acceptable for a single pedestrian because they occurred in the situations of vehicles approaching and the pedestrians stepping onto the pedestrian crossing at

Table 2: Short review of used MCDM methods in different fields.

Reference	Applied methods	Field of application
Deveci and Torkayesh, (2021)	Interval-valued neutrosophic set, which uses Shannon's entropy and mixed aggregation by comprehensive normalization technique	Selection of the most appropriate charging type for urban electric buses
Blagojević et al. (2020)	Fuzzy AHP and DEA	Measurement of the efficiency of freight transport railway undertakings
Torkayesh and Deveci (2021)	mulTi-noRmalization mUlti-distance aSsessmenT (TRUST)	Selection of the optimal battery swapping station for electric scooters
Krishankumar et al. (2021)	Attitudinal evidence-based Bayesian approach, variance approach, and (EDAS) approach	Prioritization of zero-carbon measures for sustainable urban mobility
Vesković et al. (2020)	Fuzzy PIPRECIA	Determining criteria significance in selecting reach stackers
Deveci et al. (2021)	CoCoSo with the logarithmic method and the power Heronian function	Prioritization of autonomous vehicles in real-time traffic management
Gokasar et. Al. (2021)	T2NN-based fuzzy WASPAS and TOPSIS	Rank the bridge maintenance projects
Memis et al. (2020)	Fuzzy PIPRECIA	Prioritization of road transportation risks
Simić et al. (2021)	Fermatean fuzzy set and CODAS method	Taxation of public transit investments
Nenadić (2019)	FUCOM and WASPAS	Ranking dangerous sections of the road
Simić et al. (2021)	CRITIC- and MABAC-based type-2 neutrosophic model	Public transportation pricing system selection
Pamučar et al. (2021)	Fuzzy Hamacher WASPAS decision-making model	For prioritization of sustainable supply chain of electric ferry implementation in public transportation

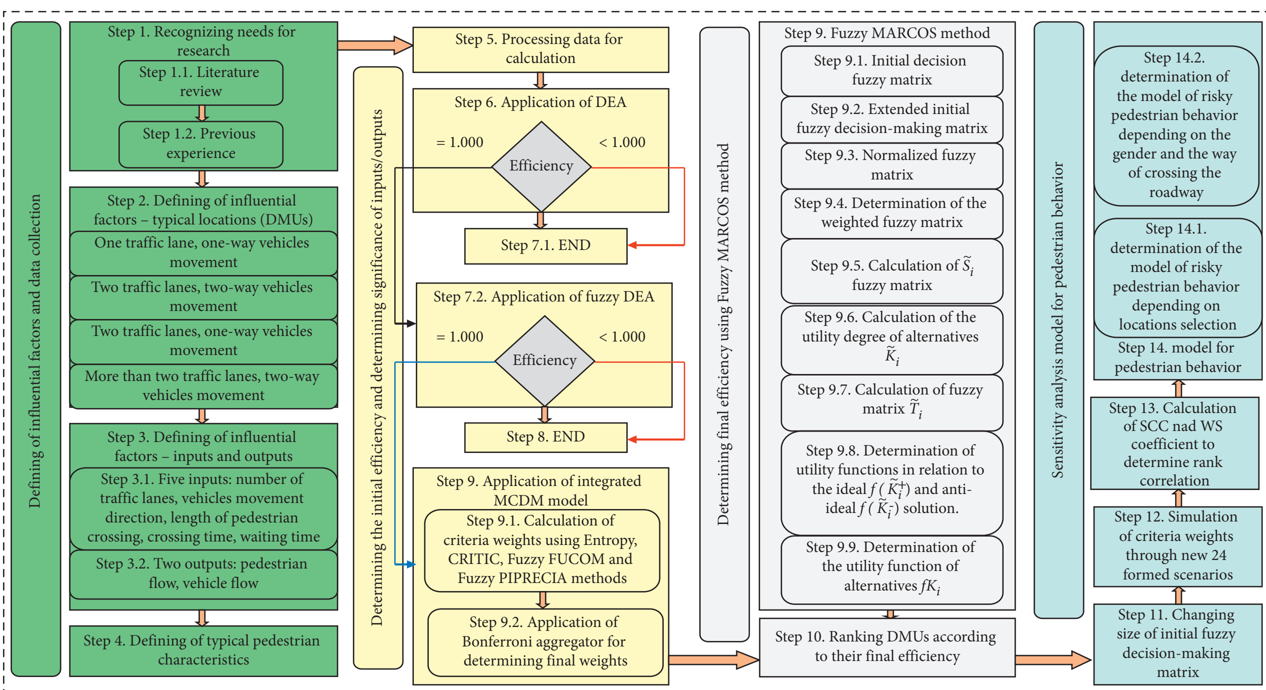


Figure 1: Research flow diagram with proposed integrated methodology.

approximately the same moment. Analogously, all accepted intervals higher than 12 s are also rejected due to the assumption that these gaps are acceptable for every pedestrian.

For every pedestrian crossing the roadway, the fact whether they did it individually or in a group was recorded, as well as whether they were male or female. When pedestrians were going across the roadway in a group, the data were established for the leading pedestrian, that is, the one who started the procedure of road crossing the first in front of the group, and the previously mentioned parameters were analysed and calculated only for them.

The analysis of the video recording and data collecting in the field resulted in the basis of about 450 intervals of pedestrians going across the roadway. Based on crossing time and the length of the pedestrian crossing, the average pedestrian velocity was calculated, as well as the pedestrian delay.

Table 3: Characteristics of the location for the analysis of pedestrian intervals.

Marking	Location name	Number of traffic lanes	Vehicles movement direction	Length of pedestrian crossing (m)	Pedestrian flow (ped/h)	Vehicle flow (PCU/h)	Level of service
K1	Fruškogorska street (1)	1	One-way	4	418	342	A
K2	Fruškogorska street (2)	2	Two-way	7	199	1092	E
K3	Braće ribnikar street	2	One-way	6	370	644	B
K4	Bulevar Kralja petra I	5	Two-way	16.5	157	1754	F

Table 4: Data obtained after recording the crossing of pedestrians at locations K1, K2, K3, and K4.

	Male	Female	One pedestrian	Group of pedestrians	Average
K1					
Waiting time (s)	1.49	0.83	1.2	1.02	1.14
Crossing time (s)	3.61	3.24	3.32	3.58	3.41
Crossing velocity (m/s)	1.13	1.29	1.25	1.16	1.22
85% Accepted (s)	7.35	6.79	7.03	7.1	7.05
85% Rejected (s)	3.16	4.31	3.6	3.5	3.338
$t_{c\ (s)}$					6.28
K2					
Waiting time (s)	4.06	3.9	3.24	6.41	3.98
Crossing time (s)	5.02	5.37	5.12	5.39	5.2
Crossing velocity (m/s)	1.5	1.4	1.48	1.34	1.45
85% Accepted (s)	8.11	6.88	7.41	8.01	7.56
85% Rejected (s)	3.797	4.66	3.79	4.67	4.115
t_c (s)					7.83
K3					
Waiting time (s)	1.74	1.04	1.26	1.81	1.42
Crossing time (s)	4.62	4.65	4.54	4.87	6.54
Crossing velocity (m/s)	1.34	1.33	1.36	1.27	1.33
85% Accepted (s)	8.11	6.88	5.881	5.803	5.862
85% Rejected (s)	3.173	2.54	2.826	3.025	2.776
$t_{c\ (s)}$					7.51
K4					
Waiting time (s)	3.21	6.5	5.13	3.53	4.56
Crossing time (s)	9.68	10	9.65	10.1	9.81
Crossing velocity (m/s)	1.74	1.71	1.77	1.65	1.73
85% Accepted (s)	7.517	6.68	7.124	7.579	7.277
85% Rejected (s)	4.192	3.608	3.773	3.925	3.802
t_c (s)					7.77

At the pedestrian crossing K1 (Fruškogorska street) during the morning peak hour (10 : 00–11 : 00), 418 pedestrians and 342 PCU/h were recorded. From the recording lasting for 1 h, altogether 95 crossings were recorded, out of which 62 crossings were by individual pedestrians, while the other crossings (33) were the crossings of groups of pedestrians. During the crossings, 108 gaps were recorded, out of which 86 accepted and 22 rejected gaps. The value of the critical interval obtained with the measured average velocity of pedestrian circulation at the location was 6.28 s.

The second typical pedestrian crossing, K2, is also in the same street, Fruškogorska street, but in the section where the two-way movement of vehicles is allowed. During the morning peak hour (10 : 00–11 : 00), 199 pedestrians and 1,092 PCU/h were recorded. The analysis of the video recording for one hour shows that there are 56 roadway crossings, out of which 43 crossings were by individual pedestrians, while the rest (13) were group crossings. A total of 107 intervals were recorded, out of which 52 were the accepted ones, and 55 were the rejected ones. The value of the critical interval obtained by the measuring the average velocity of pedestrian circulation at the given location was 7.83 s.

The third typical pedestrian crossing, K3, is in the street Braće Ribnikar. The profile of the street is such that there are two carriageway lanes separated by the divisional island with two pedestrian crossings, so that pedestrians cross the roadway in two phases. For every phase traffic flow, parameters are determined separately, such as pedestrian flow [44], vehicular flow, delays, and

Location K1 – Fruškogorska Street (1)

Location K2 – Fruškogorska Street (2)

Location K3 – Braće Ribnikar Street

Location K4 – Bulevar kralja Petra I

Figure 2: Display of the researched locations.

level of service; therefore, the interval analysis was conducted only for one phase. In that case, pedestrians cross a one-way carriageway lane with two traffic lanes. During the morning peak hour (10 : 00–11 : 00), 370 pedestrians and 644 PCU/h were recorded. The analysis of the video recording in the abovementioned period shows that there were 87 road crossings, out of which 62 were by individual pedestrians, while the rest of the crossings (25) were by group of pedestrians. During the crossings, 116 intervals were recorded, out of which 77 accepted ones and 39 rejected ones. The value of the critical interval measured by the average velocity of the pedestrian's circulation at the location was 7.51 s.

The fourth typical pedestrian crossing, K4, is in the boulevard called Bulevar Kralja Petra I. Pedestrians cross more than five traffic lanes, and vehicles go in both directions. This pedestrian crossing is typical by the fact that pedestrians use the so-called "rolling-gap" crossing method for going across the roadway. This way of crossing is typical of multilane arterials. Namely, the pedestrian starts the crossing, steps on the roadway, and pays all the attention to only one, the closest, traffic lane. With this kind of attention, the pedestrian gets to the second lane, waiting for the new acceptable interval for the crossing from the same or the opposite direction. During the morning peak hour (10 : 00–11 : 00), 157 pedestrians and 1,754 PCU/h were recorded. From the recording, which lasted for one hour, 51 crossings were recorded, out of which 33 were by the individual pedestrians, while the rest of the crossings (18) were by groups of pedestrians. During the crossings, 108 intervals were recorded, out of which 40 were the accepted ones and 68 the rejected ones. Since pedestrians in the first phase of roadway crossing pay attention only to the vehicles approaching from one direction, that is, from the left, in the analysis, it was taken into account that the value of the critical interval is calculated only for one half of the trajectory that a pedestrian is to cover. The value of the critical interval obtained by measuring the average velocity of pedestrian circulation at the location was 7.77 s. Table 4 shows all the data for all four typical locations, which are necessary for further analysis.

3.2. The Second Phase. The second phase is determining the initial efficiency and determining the significance of inputs/outputs. This phase represents the integration of several approaches into a single model to determine the efficiency of the observed locations where the research was conducted. The first step of this phase, that is, the fifth step of the overall methodology, involves the preparation and processing of data for further calculation. In the sixth step, the conventional DEA was applied (steps presented in 3.2.1) in order to determine the efficiency of the locations where the research regarding pedestrians was conducted. The algorithm is set up to react causally, which means that depending on the results of the DEA method, further steps are taken. If the results of the DEA method show that efficiency for all locations is less than 1.000, then the procedure is completed. If after the application of the DEA method, there are more than one location with efficiency = 1.000, then it proceeds to Step 7.2 in which the fuzzy DEA method is applied (steps presented in 3.2.2). After that, the procedure is the same as in the sixth step. Since the final efficiencies of all observed locations have not been obtained even when applying the fuzzy DEA method, it further implements the ninth step in which four MCDM methods for obtaining input and output weight values are integrated. There are two subjective methods in a crisp form: entropy (steps presented in 3.2.3) and CRITIC (3.2.4) and two subjective methods in a fuzzy form: fuzzy FUCOM (3.2.5) and fuzzy PIPRECIA (3.2.6). In order to obtain the final significance of the model parameters, the Bonferroni aggregator (3.2.7) was used to average the values of the criteria obtained by applying the above four methods.

3.2.1. DEA Method. This method is one of the most common methods when it comes to determining the efficiency of variant solutions [33]. It was developed by Charnes et al. [45]. this section of the study only presents the output-oriented model, which was applied to determine the efficiency of locations, that is, DMUs (decision-making units). The DEA CCR output-oriented model (max) is

$$\begin{aligned} &\mathrm{DEA}_{\mathrm{output}} = \max \sum_{i=1}^{s} w_i y_{i-\mathrm{output}} \\ &st\colon \sum_{i=1}^{m} w_i x_{ij} - \sum_{i=m+1}^{m+s} w_i y_{ij} \geq 0, \quad j = 1, \ldots, n, \sum_{i=1}^{m} w_i x_{i-\mathrm{input}} = 1 \quad w_i \geq 0, \quad i = 1, \ldots, m+s. \end{aligned} \tag{1}$$

DMU consists of m input parameters for each alternative x_{ij}, while s represents output parameters for each alternative y_{ij}, taking into account the weights of the parameters denoted by w_i. In addition, n represents the total number of DMUs.

3.2.2. Fuzzy DEA Method. This section presents an algorithm of fuzzy DEA CCR output-oriented model (max) based on linguistic variables transformed into triangular fuzzy numbers (TFNs) shown in Figure 3:

$$\begin{aligned} &\mathrm{DEA}_{\mathrm{output}} = \max \sum_{i=1}^{s} \overline{w}_i \overline{y}_{i-\mathrm{output}} \\ &st\colon \sum_{i=1}^{m} \overline{w}_i \overline{x}_{ij} - \sum_{i=m+1}^{m+s} \overline{w}_i \overline{y}_{ij} \leq 0, \quad j = 1, \ldots, n \sum_{i=1}^{m} \overline{w}_i \overline{x}_{i-\mathrm{input}} = 1 \overline{w}_i \geq 0, \quad i = 1, \ldots, m+s, \end{aligned} \tag{2}$$

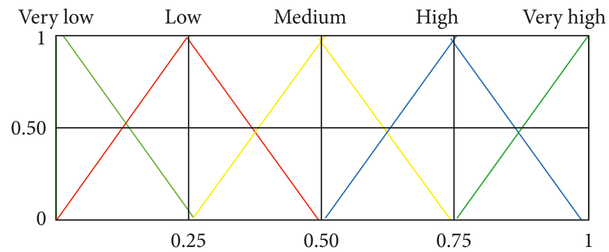


Figure 3: Fuzzy scale for the evaluation of DMUs in fuzzy DEA and fuzzy MARCOS.

where the parameters are the same as for crisp DEA, except that they are expressed in TFNs.

3.2.3. Entropy Method. The entropy method consists of the steps shown as follows [46]:

Step 1. It is necessary to normalize the initial matrix given as

$$n_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}. \tag{3}$$

Step 2. In this step, the computation of the entropy measure is performed as

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} r_{ij} \ln\left(n_{ij}\right). \tag{4}$$

Step 3. By applying this step, the values of the objective calculation of criterion weight are obtained:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n}\left(1 - e_j\right)}. \tag{5}$$

3.2.4. CRITIC Method. This method consists of the following steps [47]:

Step 1: Forming an initial matrix

$$x_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n, \tag{6}$$

where (x_{ij}) represents the characteristics of i alternative in relation to the j criterion.

Step 2: Normalization of the initial matrix depending on the type of criteria:

$$r_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad \text{if } j \in B \longrightarrow \max, \tag{7}$$

$$r_{ij} = \frac{x_{ij} - \max_i x_{ij}}{\min_i x_{ij} - \max_i x_{ij}} \quad \text{if } j \in C \longrightarrow \min. \tag{8}$$

Step 3. Determining a symmetric linear correlation matrix is as

$$r_{ij} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2} \cdot \sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}}. \tag{9}$$

Step 4. Calculation of the standard deviation (σ) is given as

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}, \tag{10}$$

where n represents the total number of data in a sample and $\overline{x}$ is the mean value of the data in a sample. And the calculation of the sum of the matrix 1-rij is given as

$$\sum_{j=1}^{n}\left(1 - r_{ij}\right). \tag{11}$$

Step 5. Determining the amount of information in relation to each criterion by

$$C_j = \sigma \sum_{j'=1}^{n} 1 - r_{ij}. \tag{12}$$

Step 6. Calculation of criterion weights is given by

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j}. \tag{13}$$

3.2.5. Fuzzy FUCOM Method. This section presents the methodology of the fuzzy FUCOM method [48]:

Step 1. Creating a set of criteria.

Step 2. Ranking the criteria based on experts' preferences by criterion importance:

$$C_{j(1)} > C_{j(2)} > \ldots > C_{j(k)}. \tag{14}$$

k denotes the ranking of the last-ranked criterion.

Step 3. Comparing the criteria using TFNs and a fuzzy linguistic scale. Referring to the criterion importance, fuzzy comparative importance $\widetilde{\varphi}_{k/(k+1)}$ is obtained using

$$\widetilde{\varphi}_{k/(k+1)} = \frac{\widetilde{\varpi}_{C_{j(k)}}}{\widetilde{\varpi}_{C_{j(k+1)}}} = \frac{\left(\varpi^{l}_{C_{j(k)}}, \varpi^{m}_{C_{j(k)}}, \varpi^{u}_{C_{j(k)}}\right)}{\left(\varpi^{l}_{C_{j(k+1)}}, \varpi^{m}_{C_{j(k+1)}}, \varpi^{u}_{C_{j(k+1)}}\right)}. \tag{15}$$

Hence, A fuzzy vector of comparative importance of evaluation criteria is obtained as follows:

$$\widetilde{\Phi} = \left(\widetilde{\varphi}_{1/2}, \widetilde{\varphi}_{2/3}, \ldots, \widetilde{\varphi}_{k/(k+1)}\right). \tag{16}$$

where $\widetilde{\varphi}_{k/(k+1)}$ is the importance of the criterion of $C_{j(k)}$ rank in comparison with the criterion of $C_{j(k+1)}$ rank.

Step 4. Calculating the optimal fuzzy weights. The final values of the fuzzy weight coefficients of the criteria $(\widetilde{w}_1, \widetilde{w}_2, ..., \widetilde{w}_n)^T$ are obtained. The final values of the weight coefficients should meet the conditions given by the following equations:

$$\frac{\widetilde{w}_k}{\widetilde{w}_{k+1}} = \widetilde{\varphi}_{k/(k+1)}, \tag{17}$$

$$\frac{\widetilde{w}_k}{\widetilde{w}_{k+2}} = \widetilde{\varphi}_{k/(k+1)} \otimes \widetilde{\varphi}_{(k+1)/(k+2)}. \tag{18}$$

$\varphi_{k/(k+1)}$ is the comparative importance of $C_{j(k)}$ and $C_{j(k+1)}$ criteria.

Then, it is required to calculate the values of the weight coefficients of the criteria $(\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n)^T$ meeting the condition that $|\widetilde{w}_k/\widetilde{w}_{k+1} - \widetilde{\varphi}_{k/(k+1)}| \le \chi$ and $|\widetilde{w}_k/\widetilde{w}_{k+2} - \widetilde{\varphi}_{k/(k+1)} \otimes \widetilde{\varphi}_{k+1/(k+2)}| \le \chi$, with the minimization of χ. Considering the above, the final nonlinear model $(\widetilde{w}_1, \widetilde{w}_2, \ldots, \widetilde{w}_n)^T$ is defined as

$$\min \chi,$$

$$\text{s.t.} \begin{cases} \left|\dfrac{\widetilde{w}_k}{\widetilde{w}_{k+1}} - \widetilde{\varphi}_{k/(k+1)}\right| \le \chi, \quad \forall j, \\ \left|\dfrac{\widetilde{w}_k}{\widetilde{w}_{k+2}} - \widetilde{\varphi}_{k/(k+1)} \otimes \widetilde{\varphi}_{(k+1)/(k+2)}\right| \le \chi, \quad \forall j, \\ \displaystyle\sum_{j=1}^{n} \widetilde{w}_j = 1, \\ w_j^l \le w_j^m \le w_j^u, \\ w_j^l \ge 0, \ \forall j, \\ j = 1, 2, \ldots, n. \end{cases} \tag{19}$$

$\widetilde{w}_j = (w_j^l, w_j^m, w_j^u)$, and $\widetilde{\varphi}_{k/(k+1)} = (\varphi^l_{k/(k+1)}, \varphi^m_{k/(k+1)}, \varphi^u_{k/(k+1)})$.

3.2.6. Fuzzy PIPRECIA Method. The fuzzy PIPRECIA method was created in the study [49] and consists of the steps presented as follows [50]:

Step 1. Forming a set of criteria and sorting the criteria according to marks from the first to the last, and this means that they need to be sorted unclassified.

Step 2. Each decision-maker individually evaluates presorted criteria by starting from the second criterion:

$$\overline{s_j^r} = \begin{cases} > \overline{1} & \text{if } C_j > C_{j-1}, \\ = \overline{1} & \text{if } C_j = C_{j-1}, \\ < \overline{1} & \text{if } C_j < C_{j-1}. \end{cases} \tag{20}$$

$\overline{s_j^r}$ denotes the assessment of criteria by a decision-maker r.

Step 3. Determining the coefficient $\overline{k}_j$ by

$$\overline{k}_j = \begin{cases} = \overline{1} & \text{if } j = 1, \\ 2 - \overline{s}_j & \text{if } j > 1. \end{cases} \tag{21}$$

Step 4. Determining the fuzzy weight $\overline{q}_j$ by

$$\overline{q}_j = \begin{cases} = \overline{1} & \text{if } j = 1, \\ \dfrac{\overline{q_{j+1}}}{\overline{k}_j} & \text{if } j > 1. \end{cases} \tag{22}$$

Step 5. Determining the relative weight of the criterion $\overline{w}_j$ by

$$\overline{w}_j = \frac{\overline{q}_j}{\sum_{j=1}^{n} \overline{q}_j}. \tag{23}$$

In the following steps, the inverse methodology of the fuzzy PIPRECIA method needs to be applied.

Step 6. Performing the assessment, but this time starting from a penultimate criterion:

$$\overline{s_j^{r'}} = \begin{cases} > \overline{1} & if \quad C_j > C_{j+1}, \\ = \overline{1} & if \quad C_j = C_{j+1}, \\ < \overline{1} & if \quad C_j < C_{j+1}. \end{cases} \tag{24}$$

Step 7. Determining the coefficient $\overline{k}'_j$ by

$$\overline{k}'_j = \begin{cases} = \overline{1} & \text{if } j = n, \\ 2 - \overline{s}'_j & \text{if } j > n. \end{cases} \tag{25}$$

Step 8. Determining the fuzzy weight $\overline{q}'_j$ by

$$\overline{q}'_j = \begin{cases} = \overline{1} & \text{if } j = n, \\ \dfrac{\overline{q'_{j+1}}}{\overline{k}'_j} & \text{if } j > n. \end{cases} \tag{26}$$

Step 9. Determining the relative weight of the criterion $\overline{w}'_j$ by

$$\overline{w}'_j = \frac{\overline{q}'_j}{\sum_{j=1}^{n} \overline{q}'_j}. \quad (27)$$

Step 10. In order to determine the final weights of criteria, it is first necessary to perform the defuzzification of the fuzzy values $\overline{w}_j$ and $\overline{w}'_j$:

$$\overline{w}''_j = \frac{1}{2}\left(w_j + w'_j\right). \quad (28)$$

Step 11. Checking the results obtained by applying Spearman and Pearson correlation coefficients.

3.2.7. Bonferroni Aggregator. In order to determine the final values of inputs and outputs that will be implemented further in the MCDM model, the Bonferroni aggregator is applied [51]:

$$a_{ij} = \left(\frac{1}{e(e-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{e} a_i^p \otimes a_j^q \right)^{1/p+q}. \quad (29)$$

In this research, e represents the number of methods used to determine the significance of the criteria, while p, $q \geq 0$ are a set of non-negative numbers.

3.3. The Third Phase. Following the previously applied methodology, explained in detail in the previous section, the final efficiency of the observed locations was determined using the fuzzy MARCOS method through the ninth step in the research diagram. After that, in the tenth step, DMUs were ranked according to their finally determined efficiency.

The fuzzy MARCOS method [52] consists of the following steps:

Step 1. Creating an initial fuzzy decision matrix.

Step 2. Expanding the previous matrix with the anti-ideal solution (AAI) as

$$\widetilde{A}(\mathrm{AI}) = \begin{cases} \min_i \widetilde{x}_{ij} & \text{if } j \in B \\ \max_i \widetilde{x}_{ij} & \text{if } j \in C, \end{cases} \quad (30)$$

and the ideal solution (AI) as

$$\widetilde{A}(\mathrm{ID}) = \begin{cases} \max_i \widetilde{x}_{ij} & \text{if } j \in B \\ \min_i \widetilde{x}_{ij} & \text{if } j \in C. \end{cases} \quad (31)$$

Step 3. Normalizing the initial fuzzy decision matrix as

$$\widetilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \left(\frac{x_{id}^l}{x_{ij}^u}, \frac{x_{id}^l}{x_{ij}^m}, \frac{x_{id}^l}{x_{ij}^l}\right) \quad \text{if } j \in C, \quad (32)$$

$$\widetilde{n}_{ij} = \left(n_{ij}^l, n_{ij}^m, n_{ij}^u\right) = \left(\frac{x_{ij}^l}{x_{id}^u}, \frac{x_{ij}^m}{x_{id}^u}, \frac{x_{ij}^u}{x_{id}^u}\right) \quad \text{if } j \in B. \quad (33)$$

Step 4. Weighting the normalized decision matrix as

$$\widetilde{v}_{ij} = \left(v_{ij}^l, v_{ij}^m, v_{ij}^u\right) = \widetilde{n}_{ij} \otimes \widetilde{w}_j = \left(n_{ij}^l \times w_j^l, n_{ij}^m \times w_j^m, n_{ij}^u \times w_j^u\right). \quad (34)$$

Step 5. Calculation of the S_i matrix is given as

$$\widetilde{S}_i = \sum_{i=1}^{n} \widetilde{v}_{ij}. \quad (35)$$

Step 6. Calculation of the degree of usefulness K_i is given as

$$\widetilde{K}_i^- = \frac{\widetilde{S}_i}{\widetilde{S}_{ai}} = \left(\frac{s_i^l}{s_{ai}^u}, \frac{s_i^m}{s_{ai}^m}, \frac{s_i^u}{s_{ai}^l}\right), \quad (36)$$

$$\widetilde{K}_i^+ = \frac{\widetilde{S}_i}{\widetilde{S}_{id}} = \left(\frac{s_i^l}{s_{id}^u}, \frac{s_i^m}{s_{id}^m}, \frac{s_i^u}{s_{id}^l}\right). \quad (37)$$

Step 7. Calculation of the fuzzy matrix $\widetilde{T}_i$ is given as

$$\begin{aligned}\widetilde{T}_i &= \widetilde{t}_i\\ &= \left(t_i^l, t_i^m, t_i^u\right)\\ &= \widetilde{K}_i^- \oplus \widetilde{K}_i^+\\ &= \left(k_i^{-l} + k_i^{+l}, k_i^{-m} + k_i^{+m}, k_i^{-u} + k_i^{+u}\right).\end{aligned} \tag{38}$$

Determining the fuzzy number $\widetilde{D}$ is given as

$$\widetilde{D} = \left(d^l, d^m, d^u\right) = \max_i \widetilde{t}_{ij}. \tag{39}$$

Step 8. Defuzzification of fuzzy numbers is given as

$$df_{\text{crisp}} = \frac{l + 4m + u}{6}. \tag{40}$$

Step 9. Determining the utility functions $f(\widetilde{K}_i)$ is given as

$$f\left(\widetilde{K}_i^+\right) = \frac{\widetilde{K}_i^-}{df_{\text{crisp}}} = \left(\frac{k_i^{-l}}{df_{\text{crisp}}}, \frac{k_i^{-m}}{df_{\text{crisp}}}, \frac{k_i^{-u}}{df_{\text{crisp}}}\right), \tag{41}$$

$$f\left(\widetilde{K}_i^-\right) = \frac{\widetilde{K}_i^+}{df_{\text{crisp}}} = \left(\frac{k_i^{+l}}{df_{\text{crisp}}}, \frac{k_i^{+m}}{df_{\text{crisp}}}, \frac{k_i^{+u}}{df_{\text{crisp}}}\right). \tag{42}$$

Step 10. Calculation of the final utility function is given as

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + 1 - f(K_i^+)/f(K_i^+) + 1 - f(K_i^-)/f(K_i^-)}. \tag{43}$$

Step 11. Ranking alternatives.

3.4. The Fourth Phase. In the last phase of the research, a sensitivity analysis and verification of previously obtained results were performed, as well as the creation of a model of pedestrian behaviour. In the eleventh step of the applied methodology, the sensitivity of the model to changing the initial matrix size was determined, while in the twelfth step, 24 new scenarios were formed in which the weight values of the criteria were simulated and the sensitivity of the model to changing the criterion significance was determined. Subsequently, in the thirteen step, rank correlations were calculated for all 24 scenarios using the Spearman correlation coefficient (SCC) and the WS coefficient. In the last fourteenth step, a model of pedestrian behaviour was created: determination of the model of risky pedestrian behaviour depending on location selection, and determination of the model of risky pedestrian behaviour depending on the gender and the way of crossing the roadway.

4. The Research Results

4.1. Application of DEA and Fuzzy DEA Methods for Determining Efficiency. As previously mentioned, the conventional DEA method was first applied to determine the efficiency of the observed locations. The model parameters that include inputs and outputs, and their measured values are presented in Table 5.

The results obtained by (1) showed that all locations, DMU1 = DMU2 = DMU3 = DMU4, have a value of 1.000, which can be observed from two aspects: that all locations are fully efficient or that conventional DEA in this case is not applicable to determine efficiency. The reason is in fact that in our example relation about required number inputs, outputs and DMUs are not satisfied. The second aspect was taken, and then, the fuzzy DEA method was applied by (2), the parameters of which were determined based on Figure 3 and Table 5, and are shown in Table 6.

The results of the applied fuzzy DEA method showed that the second location, that is, DMU2, is not efficient and then is eliminated further from the model. The results are as follows: DMU1 = 1.000, DMU2 = 0.889, $DM\ \ U3$ = 1.000, $DMU4$ = 1.000. Furthermore, the model that is solved by applying the integrated MCDM model includes three DMUs with a value of 1.000.

4.2. Application of Entropy, CRITIC, Fuzzy FUCOM, and Fuzzy PIPRECIA Methods for Determining the Significance of Inputs and Outputs. Using the entropy method, that is, Equations (3)–(5), the weight values of inputs and outputs were obtained. The complete calculation and results are shown in Table 7.

Using the CRITIC method, that is, Equations (6)–(13), the weight values of inputs and outputs were obtained. The complete calculation and results are shown in Table 8.

After applying the two methods that belong to objective methods for determining the weight values of criteria, two subjective methods in a fuzzy form were also applied. When Equations (14)–(18) are applied in the fuzzy FUCOM method, the model setting expressed by (19) is obtained:

Table 5: Measured values of inputs and outputs at four locations.

	Inputs					Outputs	
	Number of traffic lanes	Vehicles movement direction	Length of pedestrian crossing (m)	Crossing time (s)	Waiting time (s)	Pedestrian flow (ped/h)	Vehicle flow (PCU/h)
DMU1	1	1	4	3.41	1.14	418	342
DMU2	2	2	7	5.20	3.98	199	1092
DMU3	2	1	6	6.54	1.42	370	644
DMU4	5	2	16.5	9.81	4.56	157	1754

Table 6: Parameters for calculation by applying the fuzzy DEA model.

	I1	I2	I3	I4	I5	O1	O2
DMU1	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)
DMU2	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.5, 0.75, 1)
DMU3	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.25, 0.5, 0.75)
DMU4	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.75, 1, 1)

Table 7: Calculation and results obtained by applying the entropy method.

	I1	I2	I3	I4	I5	O1	O2
DMU1	1	1	4	3.41	1.14	418	342
DMU3	2	1	6	6.54	1.42	370	644
DMU4	5	2	16.5	9.81	4.56	157	1754
n_{ij}							
DMU1	0.125	0.250	0.151	0.173	0.160	0.442	0.125
DMU3	0.250	0.250	0.226	0.331	0.199	0.392	0.235
DMU4	0.625	0.500	0.623	0.496	0.640	0.166	0.640
ln (n_{ij})							
DMU1	−2.079	−1.386	−1.891	−1.757	−1.832	−0.816	−2.081
DMU3	−1.386	−1.386	−1.485	−1.106	−1.612	−0.938	−1.448
DMU4	−0.470	−0.693	−0.474	−0.700	−0.446	−1.795	−0.446
$\sum_{i=1}^{m} r_{ij} \ln (n_{ij})$	−0.900	−1.040	−0.917	−1.017	−0.900	−1.026	−0.886
e_j	0.819	0.946	0.834	0.926	0.819	0.934	0.806
$1\text{-}e_j$	0.181	0.054	0.166	0.074	0.181	0.066	0.194
$\sum_{j=1}^{n} (1 - e_j)$				0.915			
w_j	**0.197**	**0.059**	**0.181**	**0.081**	**0.197**	**0.072**	**0.212**

w_j are the weight values of inputs and outputs.

Table 8: Calculation and results obtained by applying the CRITIC method.

	I1	I2	I3	I4	I5	O1	O2
DMU1	1	1	4	3.41	1.14	418	342
DMU3	2	1	6	6.54	1.42	370	644
DMU4	5	2	16.5	9.81	4.56	157	1754
Max	5.00	2.00	16.50	9.81	4.56	418.00	1754.00
min	1.00	1.00	4.00	3.41	1.14	157.00	342.00
Normalization							
	I1	I2	I3	I4	I5	O1	O2
DMU1	1.000	1.000	1.000	1.000	1.000	1.000	0.000
DMU3	0.750	1.000	0.840	0.511	0.918	0.816	0.214
DMU4	0.000	0.000	0.000	0.000	0.000	0.000	1.000
STdev	0.520	0.577	0.537	0.500	0.555	0.532	0.527
Correlation (r_{ij})							
	I1	I2	I3	I4	I5	O1	O2
I1	1.000	0.971	0.996	0.964	0.986	0.998	−0.999
I2	0.971	1.000	0.989	0.872	0.997	0.985	−0.979
I3	0.996	0.989	1.000	0.935	0.997	1.000	−0.998
I4	0.964	0.872	0.935	1.000	0.906	0.944	−0.953
I5	0.986	0.997	0.997	0.906	1.000	0.995	−0.991

Table 8: Continued.

	I1	I2	I3	I4	I5	O1	O2
O1	0.998	0.985	1.000	0.944	0.995	1.000	−1.000
O2	−0.999	−0.979	−0.998	−0.953	−0.991	−1.000	1.000
1- r_{ij}							
I1	0.000	0.029	0.004	0.036	0.014	0.002	1.999
I2	0.029	0.000	0.011	0.128	0.003	0.015	1.979
I3	0.004	0.011	0.000	0.065	0.003	0.000	1.998
I4	0.036	0.128	0.065	0.000	0.094	0.056	1.953
I5	0.014	0.003	0.003	0.094	0.000	0.005	1.991
O1	0.002	0.015	0.000	0.056	0.005	0.000	2.000
O2	1.999	1.979	1.998	1.953	1.991	2.000	0.000
SUM	2.085	2.165	2.082	2.332	2.110	2.079	11.921
C_j	1.085	1.250	1.118	1.166	1.172	1.106	6.278
w_j	**0.082**	**0.095**	**0.085**	**0.089**	**0.089**	**0.084**	**0.476**

$$\min \chi,$$
$$\text{s.t.}\begin{cases}
\left(\frac{w_6^l}{w_7^u}-1.30\right)\le\chi;\left(\frac{w_6^m}{w_7^m}-1.40\right)\le\chi;\left(\frac{w_6^u}{w_7^l}-1.50\right)\le\chi;\left(\frac{w_7^l}{w_4^u}-0.93\right)\le\chi;\left(\frac{w7}{w_4^m}-1.07\right)\le\chi;\left(\frac{w_7^u}{w_4^l}-1.23\right)\le\chi;\\
\left(\frac{w_4^l}{w_5^u}-1.06\right)\le\chi;\left(\frac{w_4^m}{w_5^m}-1.09\right)\le\chi;\left(\frac{w_4^u}{w_5^l}-1.18\right)\le\chi;\left(\frac{w_5^l}{w_3^u}-1.00\right)\le\chi;\left(\frac{w_5^m}{w_3^m}-1.11\right)\le\chi;\left(\frac{w_5^u}{w_3^l}-1.23\right)\le\chi;\\
\left(\frac{w_3^l}{w_1^u}-1.05\right)\le\chi;\left(\frac{w_3^m}{w_1^m}-1.15\right)\le\chi;\left(\frac{w_3^u}{w_1^l}-1.26\right)\le\chi;\left(\frac{w_1^l}{w_2^u}-1.00\right)\le\chi;\left(\frac{w_1^m}{w_2^m}-1.09\right)\le\chi;\left(\frac{w_1^u}{w_2^l}-1.18\right)\le\chi;\\
\left(\frac{w_6^l}{w_4^u}-1.21\right)\le\chi;\left(\frac{w_6^m}{w_4^m}-1.50\right)\le\chi;\left(\frac{w_6^u}{w_4^l}-1.85\right)\le\chi;\left(\frac{w_7^l}{w_5^u}-0.99\right)\le\chi;\left(\frac{w_7^m}{w_5^m}-1.28\right)\le\chi;\left(\frac{w_7^u}{w_5^l}-1.66\right)\le\chi;\\
\left(\frac{w_4^l}{w_3^u}-1.06\right)\le\chi;\left(\frac{w_4^m}{w_3^m}-1.33\right)\le\chi;\left(\frac{w_4^u}{w_3^l}-1.66\right)\le\chi;\left(\frac{w_5^l}{w_1^u}-1.05\right)\le\chi;\left(\frac{w_5^m}{w_1^m}-1.28\right)\le\chi;\left(\frac{w_5^u}{w_1^l}-1.55\right)\le\chi;\\
\left(\frac{w_3^l}{w_2^u}-1.05\right)\le\chi;\left(\frac{w_3^m}{w_2^m}-1.25\right)\le\chi;\left(\frac{w_3^u}{w_2^l}-1.49\right)\le\chi;\\
\frac{\left(w_1^l+4\cdot w_1^m+w_1^u\right)}{6}+\frac{\left(w_2^l+4\cdot w_2^m+w_2^u\right)}{6}+\frac{\left(w_3^l+4\cdot w_3^m+w_3^u\right)}{6}+\frac{\left(w_4^l+4\cdot w_4^m+w_4^u\right)}{6}+\frac{\left(w_5^l+4\cdot w_5^m+w_5^u\right)}{6}+\frac{\left(w_6^l+4\cdot w_6^m+w_6^u\right)}{6}+\frac{\left(w_7^l+4\cdot w_7^m+w_7^u\right)}{6}=1;\\
w_1^l\le w_1^m\le w_1^u;w_2^l\le w_2^m\le w_2^u;w_3^l\le w_3^m\le w_3^u;w_4^l\le w_4^m\le w_4^u;w_5^l\le w_5^m\le w_5^u;w_6^l\le w_6^m\le w_6^u;w_7^l\le w_7^m\le w_7^u;\\
w_1^l,w_2^l,w_3^l,w_4^l,w_5^l,w_6^l,w_7^l\ge 0.
\end{cases} \quad (44)$$

By solving the set problem, it is obtained the fuzzy values of criteria, which are

$$\begin{aligned}
w_1&=(0.100,0.107,0.107),\\
w_2&=(0.085,0.090,0.111),\\
w_3&=(0.111,0.119,0.134),\\
w_4&=(0.143,0.148,0.175),\\
w_5&=(0.121,0.134,0.146),\\
w_6&=(0.228,0.228,0.253),\\
w_7&=(0.158,0.158,0.163).
\end{aligned} \quad (45)$$

After that, (40) is applied for defuzzification, so the following values are obtained:

$$\begin{aligned}
w_1&=0.106,\\
w_2&=0.093,\\
w_3&=0.120,\\
w_4&=0.152,\\
w_5&=0.134,\\
w_6&=0.232,\\
w_7&=0.163.
\end{aligned} \quad (46)$$

The fuzzy PIPRECIA method was used as another subjective method for determining the weight values of the criteria. Using Equations (20)–(23), the calculation shown in Table 9 was performed.

The inverse fuzzy PIPRECIA methodology, that is, Equations (24)–(27), was then applied. The results are shown in Table 10.

Table 9: Results by steps applying fuzzy PIPRECIA.

	$\bar{s}_j$	$\bar{k}_j$	$\bar{q}_j$	$\bar{w}_j$	DFwj
I1		(1, 1, 1)	(1, 1, 1)	(0.05, 0.1, 0.16)	0.103
I2	(0.5, 0.67, 1)	(1, 1.33, 1.5)	(0.67, 0.75, 1)	(0.03, 0.08, 0.16)	0.084
I3	(1.2, 1.3, 1.35)	(0.65, 0.7, 0.8)	(0.83, 1.07, 1.54)	(0.04, 0.11, 0.25)	0.121
I4	(1.3, 1.45, 1.5)	(0.5, 0.55, 0.7)	(1.19, 1.95, 3.08)	(0.06, 0.2, 0.5)	0.225
I5	(0.5, 0.67, 1)	(1, 1.33, 1.5)	(0.79, 1.46, 3.08)	(0.04, 0.15, 0.5)	0.189
O1	(1.2, 1.3, 1.35)	(0.65, 0.7, 0.8)	(0.99, 2.09, 4.73)	(0.05, 0.21, 0.77)	0.278
O2	(0.5, 0.67, 1)	(1, 1.33, 1.5)	(0.66, 1.57, 4.73)	(0.03, 0.16, 0.77)	0.240
SUM			(6.14, 9.88, 19.16)	(0.05, 0.1, 0.16)	

Table 10: Results by steps applying fuzzy PIPRECIA-I.

	$\bar{s}'_j$	$\bar{k}'_j$	$\bar{q}'_j$	$\bar{w}'_j$	Df wj
I1	(1.1, 1.15, 1.2)	(0.8, 0.85, 0.9)	(0.47, 0.38, 0.62)	(0.08, 0.08, 0.11)	0.087
I2	(0.4, 0.5, 0.67)	(1.33, 1.5, 1.6)	(0.42, 0.33, 0.49)	(0.08, 0.07, 0.09)	0.074
I3	(0.33, 0.4, 0.5)	(1.5, 1.6, 1.67)	(0.67, 0.49, 0.66)	(0.12, 0.11, 0.12)	0.110
I4	(1.1, 1.15, 1.2)	(0.8, 0.85, 0.9)	(1.12, 0.78, 0.99)	(0.2, 0.17, 0.17)	0.175
I5	(1.01, 0.5, 0.67)	(1.33, 1.5, 0.99)	(1.01, 0.67, 0.79)	(0.18, 0.14, 0.14)	0.149
O1	(1, 1, 1.05)	(0.95, 1, 1)	(1, 1, 1.05)	(0.18, 0.21, 0.19)	0.204
O2		(1, 1, 1)	(1, 1, 1)	(0.18, 0.21, 0.18)	0.202
SUM			(5.69, 4.65, 5.6)	(0.08, 0.08, 0.11)	

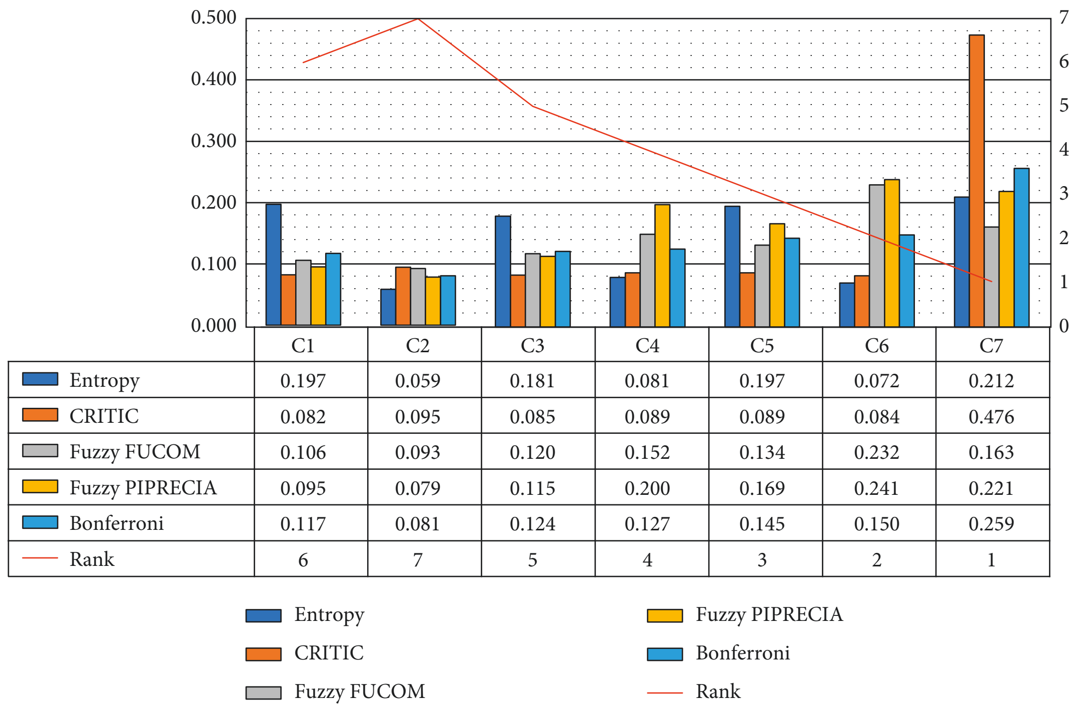
In order to calculate the final weight values of the criteria using the fuzzy and inverse fuzzy PIPRECIA methods, (29) was applied, and the following values were obtained in a crisp form because the defuzzification was previously performed using (40):

$$\begin{aligned} w_1 &= 0.095, \\ w_2 &= 0.079, \\ w_3 &= 0.115, \\ w_4 &= 0.200, \\ w_5 &= 0.169, \\ w_6 &= 0.241, \\ w_7 &= 0.211. \end{aligned} \tag{47}$$

4.3. Application of Bonferroni Aggregator for Determining the Final Values of Inputs and Outputs. Using the Bonferroni aggregator, the final values of all criteria were obtained, which is shown in Figure 4. The values are obtained as follows:

$$\begin{aligned} &\mathrm{BM}^{p=1,q=1} = (0.197, 0.082, 0.106, 0.095) \\ &\varpi_{C_1} = \left(\frac{1}{4(4-1)} \sum_{\substack{i,j=1 \\ i \neq j}}^{4} \varpi_{C_1 i}^{p} \varpi_{C_1 j}^{q} \right)^{1/1+1} = \left(0.083 \left(\begin{array}{c} 0.197^1 \cdot 0.082^1 + 0.197^1 \cdot 0.106^1 + 0.197^1 \cdot 0.095^1 \\ +0.082^1 \cdot 0.197^1 + 0.082^1 \cdot 0.106^1 + 0.082^1 \cdot 0.095^1 \\ +0.106^1 \cdot 0.197^1 + 0.106^1 \cdot 0.082^1 + 0.106^1 \cdot 0.095^1 \\ +0.095^1 \cdot 0.197^1 + 0.095^1 \cdot 0.082^1 + 0.095^1 \cdot 0.106^1 \end{array} \right) \right)^{1/1+1} \\ &= 0.117. \end{aligned} \tag{48}$$

According to the results shown in Figure 4, which were obtained by applying the integrated objective-subjective model (entropy-CRITIC-fuzzy FUCOM-fuzzy PIPRECIA, and Bonferroni aggregator), the output O2 has the highest value, that is, the seventh criterion with a value of 0.259. The second most significant parameter is the sixth criterion with



	C1	C2	C3	C4	C5	C6	C7
Entropy	0.197	0.059	0.181	0.081	0.197	0.072	0.212
CRITIC	0.082	0.095	0.085	0.089	0.089	0.084	0.476
Fuzzy FUCOM	0.106	0.093	0.120	0.152	0.134	0.232	0.163
Fuzzy PIPRECIA	0.095	0.079	0.115	0.200	0.169	0.241	0.221
Bonferroni	0.117	0.081	0.124	0.127	0.145	0.150	0.259
Rank	6	7	5	4	3	2	1

Figure 4: Final values of the criteria after the application of the subjective-objective model and the Bonferroni aggregator.

a value of 0.150. The most significant input is the waiting time at the pedestrian crossing with a value of 0.145. The least significant input is vehicles' movement direction with a value of 0.081.

4.4. Application of the Fuzzy MARCOS Method for Determining the Final Efficiency of Pedestrian Crossings.

This section presents the results obtained by applying the fuzzy MARCOS method for determining the final ranking according to the efficiency of pedestrian crossings, DMU1, DMU3, and DMU4. It is important to note that the linguistic scale from the original fuzzy MARCOS method was not used for the initial matrix, but the scale in Figure 4. Based on this scale and the data from Table 5, the extended fuzzy initial decision matrix shown in Table 11 was formed.

Since the orientation of the criteria was taken into account when evaluating DMUs by all parameters using the linguistic scale, it means that all criteria were marked as benefit further in applying the fuzzy MARCOS method and (30) and (31) were applied to extend the initial fuzzy matrix.

Equation (33) was then used to perform the normalization of the initial fuzzy matrix and (34) to calculate the weighted normalized matrix shown in Table 12.

The applying Equations (35)–(43), the results presented in Table 13 were obtained.

Based on the final efficiencies of the observed locations of pedestrian crossings obtained using the entropy-CRITIC-fuzzy FUCOM-fuzzy PIPRECIA model based on the Bonferroni aggregator and the fuzzy MARCOS method, it can be seen that the second location showed the highest efficiency in relation to the measured input-output parameters of the model. Implications of this model can be manifested through monitoring these locations in future in order to increase their efficiency, especially the worst ranked.

4.5. Testing and Verification of Results.

In this section of the study, the effect of changing the size of the initial fuzzy matrix was first tested by forming two sets in which the last-ranked DMU was eliminated from the calculation. Figure 5 shows the results obtained for this part of the model robustness testing.

From Figure 5, it can be seen that the size of the initial fuzzy matrix has no effect on changing the results in terms of the final ranking of alternatives, while their values change, but slightly.

Furthermore, the results were tested in relation to a change in the significance of the criteria; that is, a sensitivity analysis was performed. A total of 24 scenarios was formed in which new criterion values were simulated based on

$$\widetilde{W}_{n\beta} = \left(1 - \widetilde{W}_{n\alpha}\right) \frac{\widetilde{W}_{\beta}}{\left(1 - \widetilde{W}_{n}\right)}. \quad (49)$$

The 24 scenarios were formed by reducing the values of four most significant criteria by 15–90% of their own value. In scenarios S1–S6, the values of the most significant criterion, O2, were reduced. In scenarios S7–S12, S13–S18, and S19–S24, the values of criteria O1, I5, and I4 were reduced, respectively.

The results given in Figure 6 show that a change in the most significant criterion has an impact on a change in the rank of DMUs. In scenarios S2–S6, the final rank of DMUs changes because the value of the most significant criterion, O2, decreases by a range of 30–90%, which shows that the traffic flow of vehicles has an impact on the efficiency of the

Table 11: Extended fuzzy initial decision matrix.

	I1	I2	I3	I4	I5	O1	O2
AAI	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)
DMU1	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)
DMU3	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.25, 0.5, 0.75)
DMU4	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.75, 1, 1)
AI	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.75, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)

Table 12: Weighted normalized fuzzy initial decision matrix.

	I1	I2	I3	I4	I5	O1	O2
AAI	(0, 0.03, 0.06)	(0.02, 0.04, 0.06)	(0, 0.03, 0.06)	(0, 0.03, 0.06)	(0, 0.04, 0.07)	(0, 0.04, 0.08)	(0, 0.06, 0.13)
DMU1	(0.09, 0.12, 0.12)	(0.04, 0.06, 0.08)	(0.09, 0.12, 0.12)	(0.1, 0.13, 0.13)	(0.11, 0.15, 0.15)	(0.11, 0.15, 0.15)	(0, 0.06, 0.13)
DMU3	(0.06, 0.09, 0.12)	(0.04, 0.06, 0.08)	(0.06, 0.09, 0.12)	(0.06, 0.1, 0.13)	(0.11, 0.15, 0.15)	(0.11, 0.15, 0.15)	(0.06, 0.13, 0.19)
DMU4	(0, 0.03, 0.06)	(0.02, 0.04, 0.06)	(0, 0.03, 0.06)	(0, 0.03, 0.06)	(0, 0.04, 0.07)	(0, 0.04, 0.08)	(0.19, 0.26, 0.26)
AI	(0.09, 0.12, 0.12)	(0.04, 0.06, 0.08)	(0.09, 0.12, 0.12)	(0.1, 0.13, 0.13)	(0.11, 0.15, 0.15)	(0.11, 0.15, 0.15)	(0.19, 0.26, 0.26)

Table 13: Final results obtained by applying the integrated model.

	$f(\tilde{K}_i^-)$	$f(\tilde{K}_i^+)$	K-	K+	fK-	fK+	Ki	Rank
DMU1	(0.05, 0.08, 0.11)	(0.1, 0.27, 4.05)	9.330	0.823	0.077	0.872	0.772	**2**
DMU3	(0.05, 0.07, 0.12)	(0.09, 0.26, 4.35)	9.788	0.815	0.076	0.915	0.802	**1**
DMU4	(0.02, 0.04, 0.08)	(0.04, 0.16, 3.01)	6.589	0.499	0.047	0.616	0.321	**3**

The bold values are final ranking of DMUs (decision making units), which are in fact the locations of pedestrian crossings.

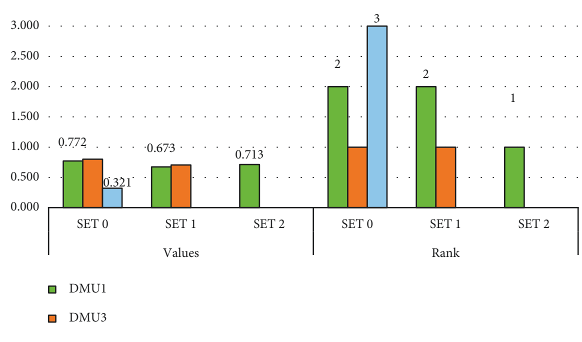


Figure 5: Testing the results depending on the size of the initial fuzzy decision matrix.

observed locations of pedestrian crossings. In other scenarios, when the values of other criteria are reduced, there is no change in the final ranks. Due to the occurrence of the change in ranks, rank correlations were then calculated for all 24 scenarios using the Spearman correlation coefficient (SCC) and the WS coefficient [53].

Figure 7 shows the rank correlation calculated by changing the SCC and WS coefficients. For all rank changes in scenarios S2–S6, the correlation coefficient is 0.500, while in other scenarios, there is a total rank correlation. Observing the average total value of rank correlation with a value of 0.896, it can be concluded that there is a large correlation.

4.6. Comparative Analysis of Pedestrian Intervals. The obtained results served as a basis for the comparative analysis of pedestrian intervals, whereby it was assumed that the values of pedestrian intervals are different types of pedestrian crossings, which were divided into four typical ones. Also, it is assumed that there are different relations in values between the accepted, the rejected, and the critical intervals depending on the type of the pedestrian crossing. Typical pedestrian crossings were chosen on the basis of the number of lanes the pedestrian has to cross, as well as of the direction of the vehicle approaching to the pedestrian crossing. In accordance with similar research studies [16, 17], the values of 85% of the accepted intervals are taken as the representative values. Also, it was established that the accepted intervals behave by normal distribution and the rejected ones by log-normal distribution.

Figure 8 shows the cumulative distribution of the accepted intervals, for each typical location separately.

Figure 9 shows the cumulative distribution of the rejected intervals, for each typical location separately.

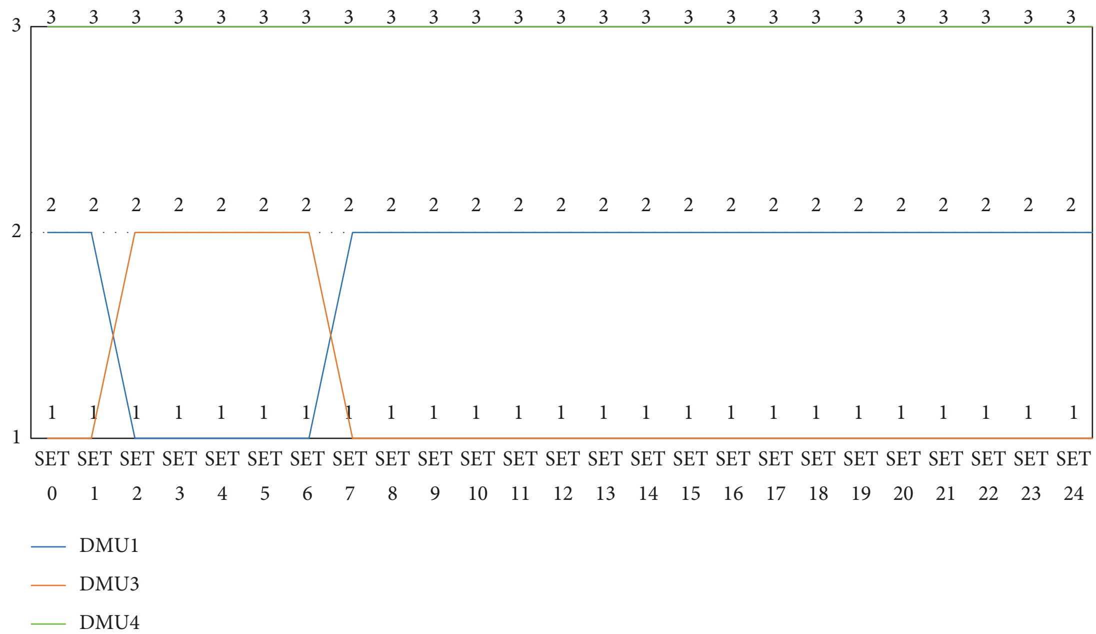
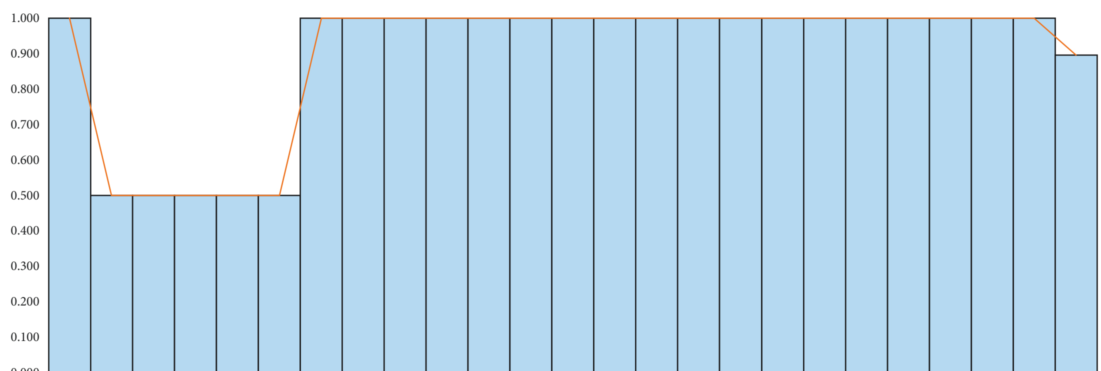


Figure 6: Ranks of alternatives in relation to 24 newly formed scenarios.



	SET1	SET2	SET3	SET4	SET5	SET6	SET7	SET8	SET9	SET10	SET11	SET12	SET3	SET14	SET15	SET16	SET17	SET18	SET19	SET20	SET21	SET22	SET23	SET24	AV
SCC	1.000	0.500	0.500	0.500	0.500	0.500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.896
WS	1.000	0.500	0.500	0.500	0.500	0.500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.896

Figure 7: Calculation of SCC and WS coefficients for determining rank correlation.

Figure 10 shows the comparative display of cumulative distribution of the accepted intervals at the chosen typical locations K1, K2, K3, and K4.

As it can be seen in Figure 10, the shortest accepted intervals were recorded the location K3 (5.86 s), where the pedestrians were crossing two traffic lanes, and the vehicles were approaching only from one direction. The explanation for this occurrence is in the fact that the pedestrian crossing K3 represents the so-called boulevard type of pedestrian crossings, where pedestrians cross the roadway in two phases, whereby between the traffic lanes of the opposite vehicles' movement directions, there is a divisional island. During the accepted intervals recording, not only the crossings of the pedestrians who start the first phase but the crossings that were a part of the second phase of crossing were considered. Namely, the analysis of the behaviour of pedestrians during roadway crossing showed that pedestrians in the first phase already pay attention to the vehicles, which are conflicting for their crossing in the second phase. In that way, pedestrians have more time for the assessment, they have more confidence, they are more visible to the drivers since they have already started moving, and for these reasons, they choose shorter intervals for crossing the roadway. At other locations, approximately the same values of the accepted intervals were recorded. At crossing K1, pedestrians were crossing only one traffic lane, whereby the vehicles were approaching only from one direction. The value of the accepted intervals at this location was 7.05 s. At the crossing K4 (more than two traffic lanes, two-way direction of vehicles movement), the value of the accepted intervals was 7.28 s. The longest accepted pedestrian intervals were noticed at crossing K2 (7.56 s). At that location,

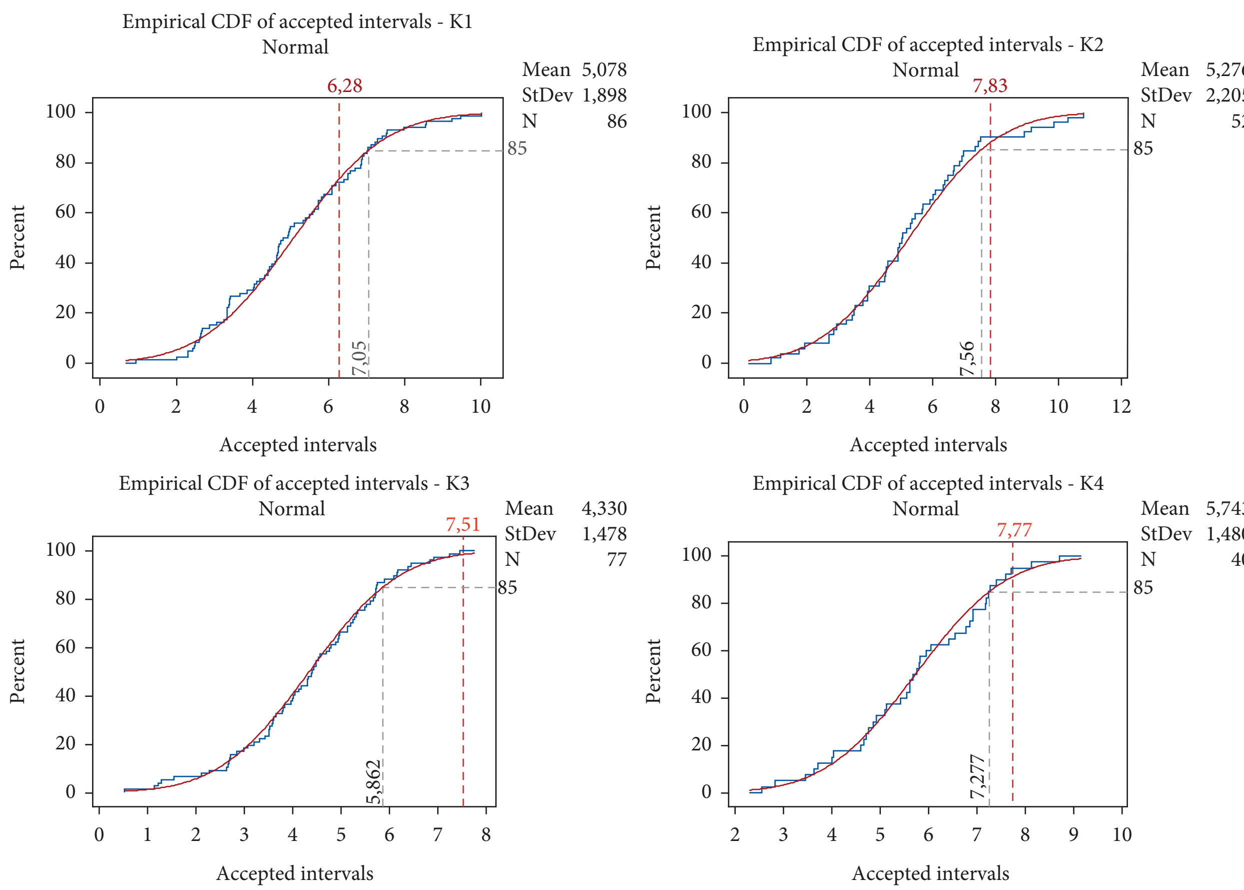


FIGURE 8: Cumulative distribution of the accepted intervals by locations.

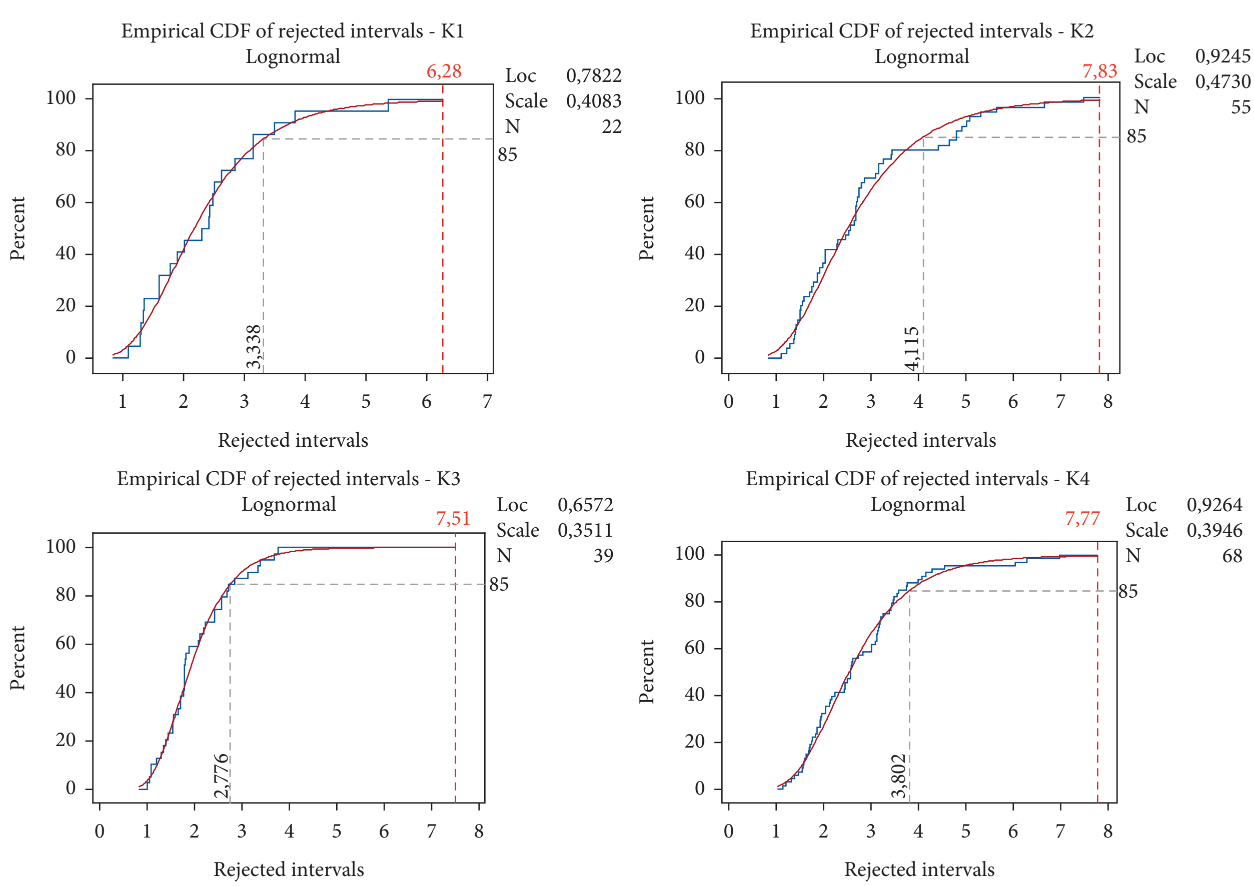


FIGURE 9: Cumulative distribution of the rejected intervals by locations.

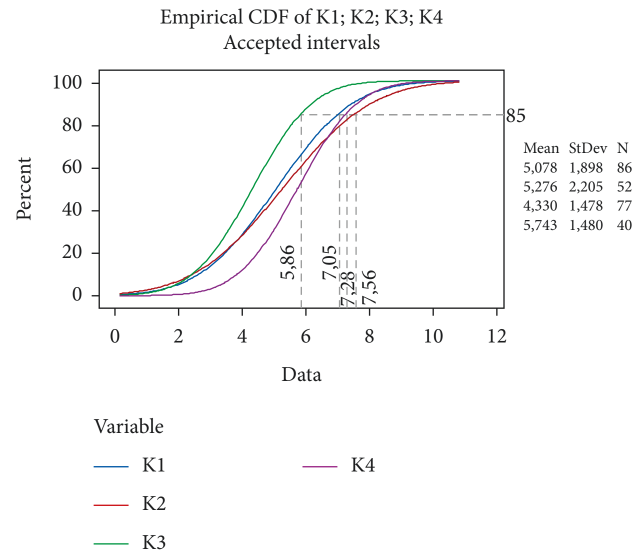


Figure 10: Comparative display of cumulative distribution of the accepted intervals for four typical pedestrian crossings.

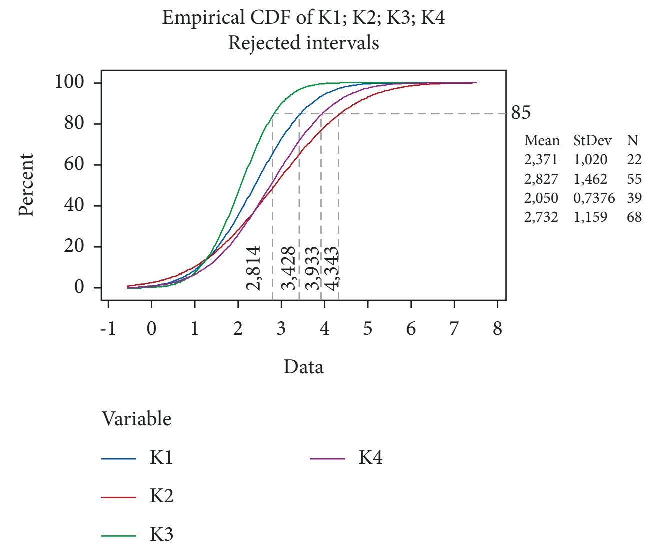


Figure 11: Comparative display of cumulative distribution of the rejected intervals for four typical pedestrian crossings.

pedestrians go across two traffic lanes, and vehicles approach from both directions. The explanation for the longest intervals is in the fact that when pedestrians go across the roadway, they have to pay attention to the vehicles approaching from both directions, and for these reasons, they are more careful and indecisive when choosing the interval. When they cross the roadway at this type of pedestrian crossing, pedestrians have to choose an interval of sufficient length in order to avoid the conflict with vehicles approaching from both directions, unlike at previous types of pedestrian crossings, where vehicles were approaching only from one direction. As previously mentioned, at location K4, although there is two-way direction movement of vehicles, due to "rolling-gap" crossing the roadway by pedestrians, intervals were chosen by the assessment of the movement of vehicles approaching from only one direction, that is, during the first phase of the roadway crossing.

Based on the research results, a comparative analysis of the rejected intervals at typical locations was conducted, whereby the obtained results are similar to those in the case of the accepted intervals (Figure 11). The longest rejected intervals were noticed at location K2 (3.343 s), while the shortest rejected intervals were at location K3 (2.814 s), which confirmed the assumptions about the influence of previously described traffic conditions at pedestrian crossings on the value of the interval when crossing the roadway.

In order to compare the values of the critical, rejected, and accepted intervals, critical intervals were calculated for each of the locations, as well as 85% of the values of the accepted and rejected intervals (Figure 12). Highway Capacity Manual (HCM) defines the critical interval as the time expressed in seconds within which the pedestrian will not start going across the pedestrian crossing. Thus, critical time interval represents the minimum necessary time during which the pedestrian can cross the roadway. Of all analysed locations, only at location K1, 85% of the value of the accepted intervals was higher than the value of the critical

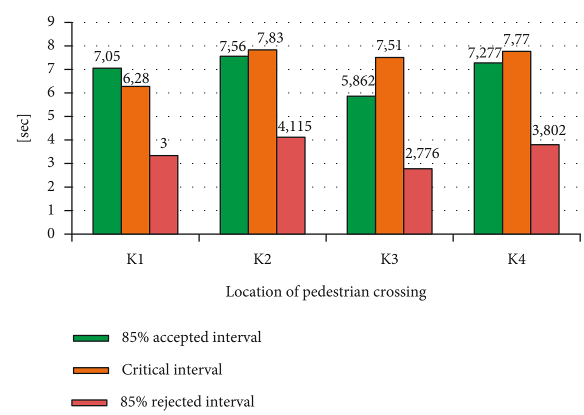


Figure 12: Value of the accepted, rejected, and critical intervals at typical locations of pedestrian crossings.

interval, which practically means that a certain number of pedestrians choose the intervals for crossing that are longer than the critical one, therefore safer for crossing. At all other locations, 85% of the value of the accepted intervals is lower than the critical intervals determined by the HCM method.

The biggest difference between the accepted intervals and critical intervals is noticed at location K3, where 85% of the value of the accepted interval is 5.86 s, and the critical interval is 7.51 s. The explanation for this occurrence is similar to the case when at the same location, the lowest value of the accepted intervals out of all observed locations was recorded. Namely, parts of pedestrians who start the second phase of crossing the roadway, in the first phase assess the distance and the velocity of the approaching vehicles. Pedestrians at the same time also have their own velocity of movement, which makes them more noticeable to drivers than in the case when they stand and assume that in that case, drivers will react to reduce the velocity so as to avoid the conflict. The lowest difference between the accepted and critical intervals is at location K2 (difference of 0.27 s), whereby the difference of the accepted intervals is approximately the same as the time, which is, by calculations, necessary for the pedestrians to reach the other side of the roadway.

After the analysis, it can be concluded that the values of the accepted and critical intervals imply that the behaviour of some pedestrians is risky, which is reflected in accepting the intervals, which are not completely safe for crossing the roadway. Figure 13 shows the percentage of pedestrians who chose an interval that is smaller or larger than the critical interval.

At location K1, in relation to the critical interval ($t_c = 6.28$ s), it was established that 73.7% of pedestrians choose the intervals that are shorter than the time necessary for crossing to the other side of the roadway. It means that only 26.3% of pedestrians choose the intervals that are longer than the critical ones, whereby safer for going across the pedestrian crossing. This result is a possible consequence of the fact that, at this pedestrian crossing, pedestrians go across only one traffic lane and they pay attention and assess the approaching of the vehicles only from one direction.

The lowest percentage of the pedestrians who chose the intervals higher than the critical one, only 1.6%, was recorded at location K3. At this pedestrian crossing, pedestrians cross two traffic lanes, while vehicles approach the pedestrian crossing from both sides. Considering the research results, this location has the highest percentage of unsafe crossings of pedestrians.

Figure 13: Comparative display of the accepted intervals of pedestrians and critical intervals at typical locations.

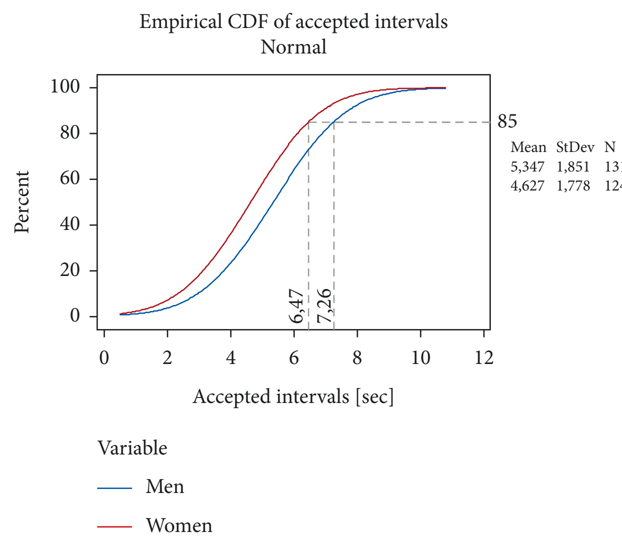


Figure 14: Cumulative distribution of the accepted intervals in relation to the gender of pedestrians at all locations altogether.

4.7. The Accepted Intervals Depending on the Pedestrian's Gender. During the analysis of the accepted intervals depending on the gender of pedestrians, 255 crossing of pedestrians were considered, at four locations, out of which 131 pedestrians were male (51%) and 124 pedestrians were female (49%).

Figure 14 shows united data of cumulative distribution of the accepted intervals for all four locations; 85% of the value of the accepted intervals for women is 6.47 s and for men 7.26 s. Figure 14 shows the cumulative distributions of the accepted intervals depending on the gender of the individual pedestrian by locations. Apart from 85% of the value of the accepted intervals for men and women, the figure also shows the values of critical intervals calculated for each typical location.

What is common for all the locations is the fact that female pedestrians choose shorter intervals for crossing the roadway, which confirms the assumption that the gender of pedestrians has an influence on the choice of crossing interval.

Based on the data collected at four locations, the average waiting time was calculated as well as the average velocity of pedestrian's going across the roadway in relation to the gender. The analysis results showed that the waiting time of the male pedestrians is 2.4 s/pedestrian, while for female ones, the obtained value was slightly lower and it is 2.35 s/pedestrian. The pedestrian velocities are identical, regardless of the gender: in average, they are both for men and women 1.39 m/s, which represents the velocity, which is higher than the recommended value by HCM (1.2 m/s). It is higher than the value that is adopted when pedestrian crossing signals are designed in the Republic of Serbia (from 0.8 m/s to 1.2 m/s) and that depends on the character and the size of the pedestrian flows, as well as on the way of regulation of pedestrian traffic, which is applied [54].

4.8. The Accepted Intervals Depending on the Type of Crossing the Roadway. During the analysis of the accepted intervals depending on the type of crossing the roadway, 255 crossings of pedestrians were taken into account, both individual and group ones, at 4 typical locations, out of which 177 were the crossings by individuals (69%) and 78 were group crossings (31%). Figure 15 shows the data consolidation regarding cumulative distribution of the accepted intervals for all four locations; 85% of the value of the accepted intervals for pedestrians who individually cross the roadway is 6.85 s, and for the pedestrians who cross the roadway in groups, it is 7.04 s (Figure 16). Figure 17 shows cumulative distributions of the accepted intervals depending

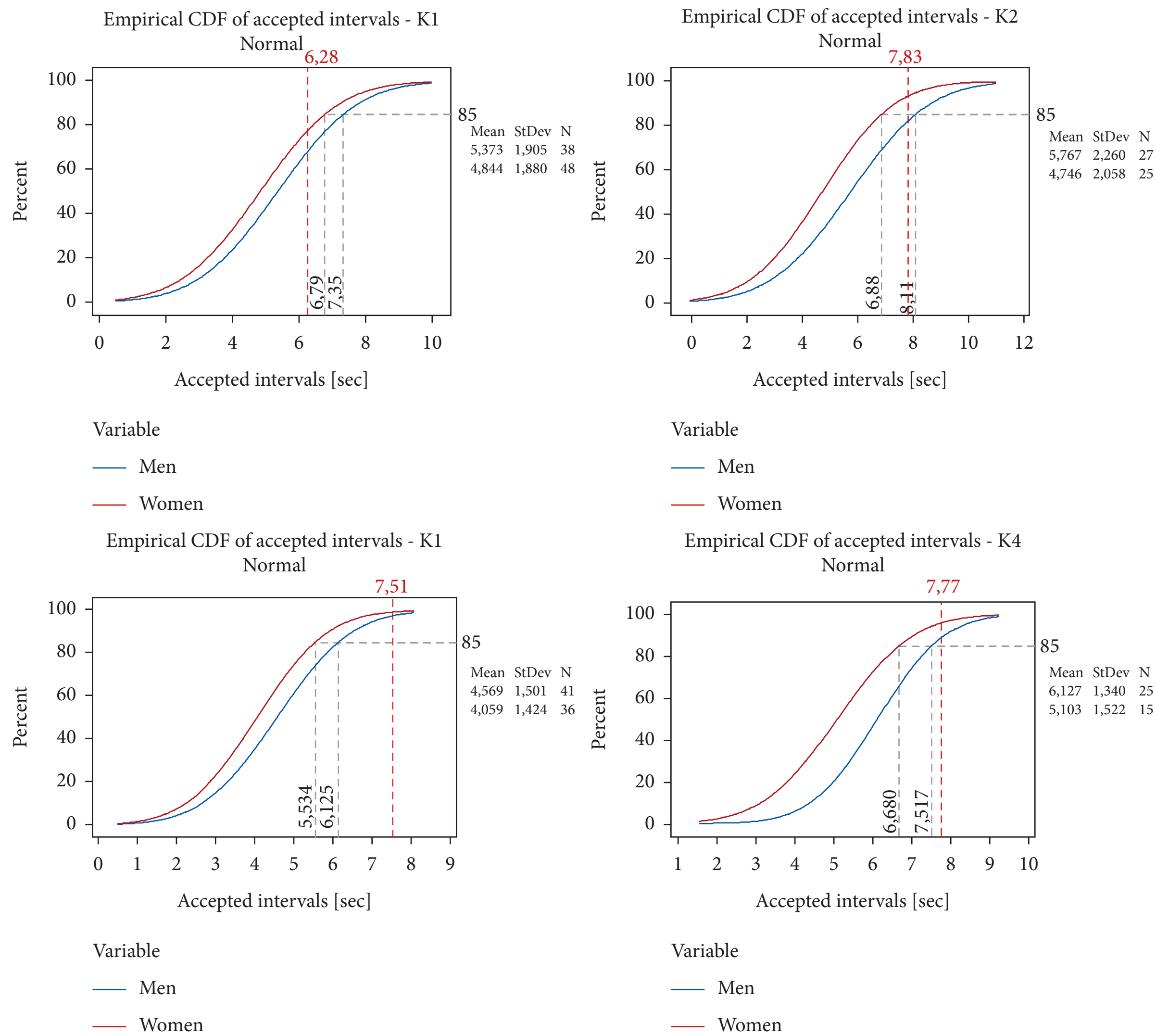


FIGURE 15: Cumulative distribution of the accepted intervals in relation to the pedestrian's gender at the locations K1–K4.

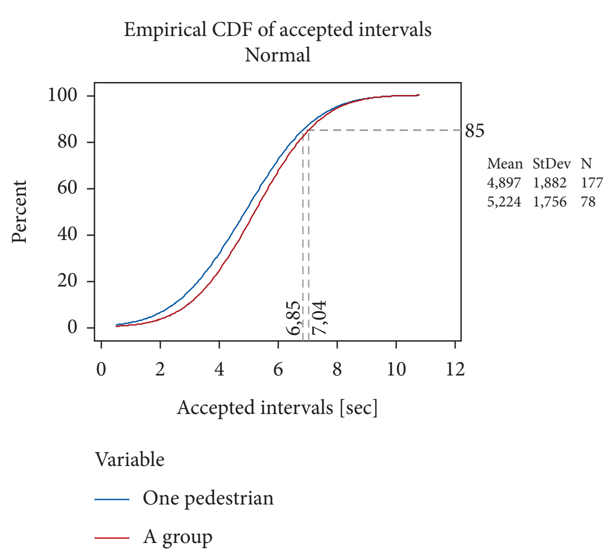


FIGURE 16: Cumulative distribution of the accepted intervals in relation to the type of crossing for all locations altogether.

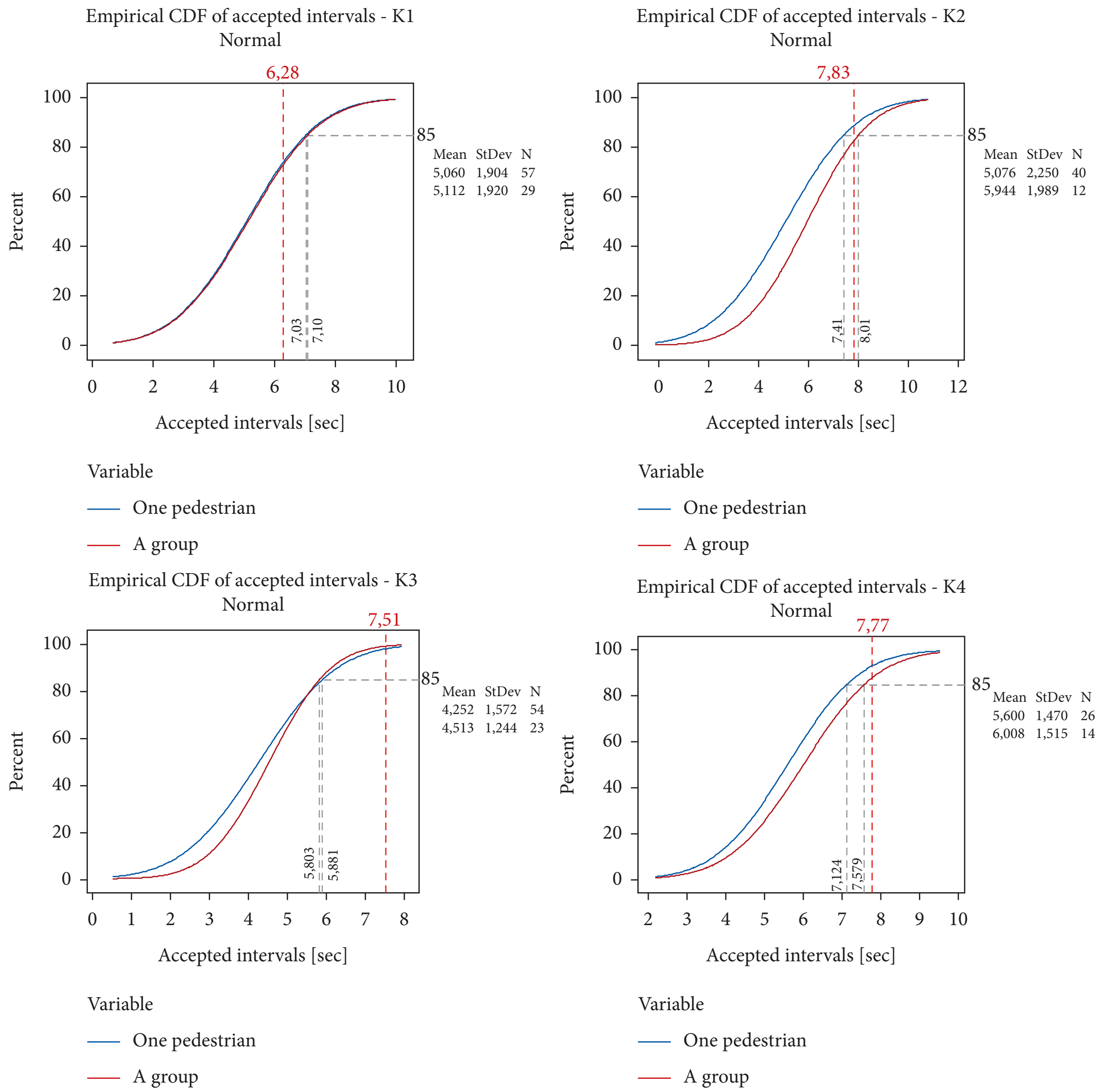


Figure 17: Cumulative distribution of the accepted intervals in relation to the type of crossing at typical locations K1, K2, K3, and K4.

on the type of the crossing individually by locations. Apart from 85% of the value of the accepted intervals for crossing the roadway by an individual pedestrian and groups of pedestrians, the flow charts show the values of critical intervals, which are calculated for each typical location.

What is common for all locations is when pedestrians cross the roadway alone, they choose shorter intervals, in comparison with the crossing in a group, when they choose longer intervals. The analysis results confirm the assumption that the type of crossing affects the length of the accepted interval for crossing the roadway.

Based on the data collected at four locations, the average waiting time was calculated, as well as the average speed of pedestrians' going across the roadway in relation to the type of crossing. The analysis results show that the waiting time of the pedestrian standing alone at the edge of the roadway is 2.3 s, while for a group of pedestrians, the average waiting is longer and it is 2.54 s/pedestrian. The velocities of pedestrians depending on the type of crossing differ, and for individual pedestrians, it is 1.42 m/s, while the average velocity for the group is 1.31 m/s.

5. Discussion

Starting from initial assumptions, the analysis of pedestrian intervals during crossing the roadway was conducted. Around 450 intervals were analysed (accepted and rejected) at four typical locations. Statistical analysis showed that the accepted intervals behave by the normal distribution and the rejected ones by log-normal distribution, which is in accordance with the previous research studies conducted in this area [9, 12, 16, 55]. The results showed that the accepted intervals differ in relation to the characteristics of the location (number of lanes, which a pedestrian has to cross, and the direction of the approaching vehicles towards the pedestrian crossing). The analysis established that in many cases, pedestrians choose the interval, which is shorter than the critical one, and they create different risky traffic situations. According to the analysis results, the type of the location, which has the highest percentage of unsafe crossings of pedestrians, is the pedestrian crossing at the two-way road with two lanes, when pedestrians cross two traffic lanes, and vehicles approach the pedestrian crossing from both sides.

Apart from the characteristics of the location, pedestrian intervals were analysed from the aspect of gender characteristics of pedestrians (men and women) and the type of crossing the roadway (crossing of the individual and of a group of pedestrians). What is common for all the locations is that pedestrians of the female gender choose shorter intervals for crossing the roadway. It means that pedestrians of the male gender are less prone to risk than women and they choose longer intervals. This result is in accordance with the research studies carried out on the territory of Europe [9], while the research carried out on the territory of Asia showed that men choose shorter intervals for crossing in comparison with women [11–13].

Analysis of the average velocities of pedestrians when crossing the roadway showed that there are no significant differences in average values of velocities regarding the gender (1.39 m/s), which was proved in research studies [16, 46]. However, most authors came to conclusion that the velocity of male pedestrians is slightly higher than that of female pedestrians [22, 23, 56]. Similar results were obtained with the waiting time: in research studies carried out mostly on the territory of Asia, the waiting time for male pedestrians is shorter in comparison with women [21, 56, 57]. The research results for the needs of this article showed that the average waiting time of pedestrians is approximately the same in relation to the gender: for men, it is 2.4 s, while for women, it is 2.35 s.

The analysis results show that the type of crossing (individual crossing or a group of pedestrians) affects the length of the accepted interval for crossing the roadway also by the fact that pedestrians who are in a group choose longer intervals (7.04 s) in comparison with individual roadway crossings (6.85 s). The same conclusions were reached by the authors of one of the rare research studies from this field conducted in Europe [9], while the research conducted on the territory of Asia showed the opposite results [24, 25]. However, during the analysis of the velocities of pedestrians' circulation, the results showed that the velocity of the pedestrians who cross the roadway individually is higher (1.42 m/s) in comparison with the velocity of the group of pedestrians (1.31 m/s). This is in accordance with most research studies conducted in the world regarding velocity of the pedestrians when crossing the roadway [20, 23, 58]. In accordance with the stated, it was established that the average waiting time of a group of pedestrians is longer than the waiting time of an individual pedestrian (2.54 s in relation to 2.3 s).

Proximity to facilities such as schools, preschools, and eldercare facilities significantly affects the structure of pedestrians at the pedestrian crossing. Different categories of traffic participants have different speeds, but also different psychophysical abilities on which their behavior in traffic depends. The ability of different groups of pedestrians to select appropriate intervals depends on their ability to estimate the speed of an oncoming vehicle and the time it takes them to cross the pedestrian crossing. In addition, the location of the pedestrian crossing can be observed from the point of view of geometry, that is, the type of road construction. In that case, there are two basic types of location: crossing at intersections and crossing at a mid-block crossing. The geometric characteristics of the road affect the crossing from the aspect of the spatial distance that the pedestrian has to overcome. The number of traffic lanes is a very important factor due to the distance that pedestrians cross, because with the increase in the number of traffic lanes, the need for the introduction of refuge islands increases. Knowing the structure of pedestrians by some of the aforementioned categories, as well as the geometry of the intersection on a larger sample of locations, would certainly give a more precise picture and more detailed analysis that could form models for a specific category of participants and location of pedestrian crossing depending on geometry.

6. Conclusion

With the assumption that factors like traffic conditions at the pedestrian crossing, the characteristics of pedestrians and the number of pedestrians who in a group cross the roadway, affect the length of the accepted intervals, the analysis of four typical locations of pedestrian crossings was conducted. An original integrated multiphase model for determining the efficiency of pedestrian crossings was created. First, the DEA method was applied in a crisp form, which showed that all locations were efficient. Due to the drawback of the classical DEA method manifested in this article too, the fuzzy DEA method was applied, the results of which show that the second location is not efficient in terms of the observed parameters. In order to determine the final efficiency, the fuzzy MARCOS method was applied. Before that, it was integrated an objective-subjective model for determining the weights of the criteria based on the Bonferroni aggregator for averaging and obtaining final values. Four methods were applied: entropy, CRITIC, fuzzy FUCOM, and fuzzy PIPRECIA. The created multiphase model that treats objectivity and subjectivity can be applied in future for different studies.

The analysis results showed that the accepted intervals differ in relation to the characteristics of the locations (number of lanes, which a pedestrian has to cross, and the direction of the approaching vehicles in relation to the pedestrian crossing). The shortest accepted intervals were recorded at the pedestrian crossing where pedestrians cross two traffic lanes with vehicles approaching from one direction. At this location, the percentage of the accepted intervals, which are shorter than the critical interval, was the highest, which implies that pedestrians at this type of pedestrian crossing create different risky situations when crossing the roadway.

The analysis of the accepted intervals at all locations showed that women choose shorter intervals in relation to men, but there were no significant differences in the average values of the crossing velocities and waiting time at the pedestrian crossing. Observing the number of pedestrians in a group who cross the roadway, it was noticed that pedestrians who cross the roadway alone choose shorter intervals for crossing, they move faster when crossing the roadway, and they wait shorter for the adequate crossing interval. The obtained results are in accordance with the research studies conducted on the territory of Europe [9, 10], while the research studies conducted on the territory of Asia showed opposite results [12, 22, 23, 56].

Analysis results regarding pedestrians' behaviour during roadway crossing showed in the article imply the basic characteristics of pedestrians' behaviour noticed in local traffic conditions. Some of the limitations in the research are the small number of considered pedestrian crossing locations, as well as the limitation in the initial phase of the model when the DEA model is applied, and the ratio of the number of inputs, outputs, and DMUs. With the application of the defined model, the future research could be performed by the evaluation of the influence and specific conditions of the local environment (school zones, zones with greater attraction, slow traffic zones), as well as traffic flow characteristics (speed, flow, density) and different categories of pedestrians as traffic participants (children, the elderly, people with disabilities, mothers with children), which has not been the case so far. That would contribute to a more precise determination of the level of service at different types of pedestrian crossings as well as to defining special measures in the field of pedestrian traffic, in order to achieve a sustainable and safe traffic system in cities. The recommendations for future works from this field should be determining the influence of other factors (drivers' behaviour, vehicles' characteristics, road geometry, built street environment, etc.) on the behaviour of pedestrians during roadway crossing. Special attention should be paid to vehicle category, vehicle position in the traffic lane, number of traffic lanes, presence of illegal parked cars, motorist yield rate, and pedestrian crossing designs and equipment. The pedestrian's accepted gaps have a unique set of conditions, which can be used in statistical analysis. In such a way, certain models can be modelled, and they can be used for evaluating the probability of the accepted crossing gap, which has not been carried out so far at pedestrian crossings in the city of Novi Sad. The application of the models and recommendations that are the results of the research will enable experts in this field to obtain the results that correspond to the actual traffic conditions in the process of analysing the level of service at pedestrian crossings. Accordingly, it will be easier to choose appropriate measures in the field of traffic engineering in order to improve traffic conditions and safety of all participants in the traffic system. Implications of this model can be manifested through monitoring these locations in future in order to increase their efficiency, especially the worst ranked.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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