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# Urban Evaluation of Pedestrian Crossings Based on Start-Up Time Using the MEREC-MARCOS Model

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**Abstract:** In urban areas, the confluence of pedestrian and vehicular flows at intersections necessitates systemic approaches to optimize pedestrian movement and safety at signalized crossings. This study focuses on evaluating the impact of pedestrian start-up time on the efficiency of pedestrian flow at such intersections, utilizing the integrated Method based on the Removal Effects of Criteria (MEREC) and Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) model. The research was conducted across five cities in Bosnia and Herzegovina and Serbia, analyzing how variations in start-up time, influenced by different age groups, contribute to overall time losses and, consequently, affect the level of service of pedestrian flows. Criterion values were determined using the objective MEREC method, while the MARCOS method facilitated the evaluation of the cities in question. Both early and delayed pedestrian start-up times were examined, with findings presented through the 85th percentile. Data collection was carried out under actual traffic conditions at signalized intersections, during peak hours, focusing on pedestrians positioned at the front line adjacent to the roadway. The intersections' diverse geometric and spatial characteristics were also considered. The results revealed significant variations in pedestrian start-up times among the top three evaluated cities (Doboj, Sarajevo, and Novi Sad), highlighting the model's sensitivity to input parameters. This study underscores the necessity for tailored traffic regulation strategies to mitigate time losses at pedestrian crossings, ultimately enhancing pedestrian flow quality at signalized intersections.

**Keywords:** Start-up time; Pedestrian crossings; Early start-up; Delayed start-up; Method based on the Removal Effects of Criteria (MEREC); Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS)

## 1 Introduction

Walking represents an unavoidable type of movement for all traffic participants, as every type of traffic includes a component of pedestrian movement. Depending on the volume for vehicle and pedestrian flows at intersections and designated pedestrian crossings, the right of way in areas marked with pedestrian crossings is usually regulated by traffic lights. Traffic lights primarily aim to control the interaction between pedestrians and vehicles. However, the occurrence of time losses at signalized intersections and pedestrian crossings can significantly affect the time and, therefore, the attractiveness and quality of walking and pedestrian flows.

Pedestrians are usually the least protected traffic participants, making them more exposed to the risk of traffic accidents than other participants. Crossing roads poses the greatest risk to pedestrians, given the potential danger of conflicts with motor vehicles in such situations. The level of service for pedestrian flows is primarily determined based on flow, pedestrian flow speed, and the space or area allocated to pedestrians. Methods for analyzing the level of service on pedestrian roadways, according to the HCM 2010 [1],ncompass a series of steps requiring input data related to traffic and pedestrian flow intensity, geometric conditions, and the degree of vehicle yield to pedestrians.

The time required for pedestrians to cross the pedestrian crossing depends on pedestrian speed (pedestrian flows) and the length of the pedestrian crossing. The total time required for a pedestrian to cross the roadway consists of the time needed to cross the pedestrian crossing and the pedestrian start-up time. Pedestrian start-up time is the period from when the green signal, i.e., pedestrian phase, is activated until pedestrians' step from the sidewalk onto the roadway. If a pedestrian steps onto the roadway during the red signal, then the start-up time is considered negative and is known in the literature as the early start-up time. When a pedestrian steps onto the roadway after the green signal is activated, the start-up time is considered positive and is known as the delayed start-up time.

Unfortunately, most signal timing calculations do not consider the start-up time, even though it is one of the main factors affecting the total crossing time. The early start-up time exposes pedestrians to danger as there is a possibility of conflicts between pedestrians and vehicles, while the delayed start-up time affects the overall crossing time of pedestrians and affects other pedestrians lined up behind them to cross the roadway. Pedestrian Level of Service (PLOS) assessment is the most common approach for evaluating the service quality of a pedestrian crossing.The aim of this paper is to evaluate five different cities with signalized intersections without counters based on start-up time, depending on the age structure of pedestrians. Through the aim of the paper and based on previously collected data from a large sample, it is necessary to determine pedestrian behavior in different cities, and which structure has the most influence on the possibility of conflicts between pedestrian flows and vehicle flows

Following the introductory section, a brief section delves into the state-of-the-art analysis. Section 3 outlines the MEREC and MARCOS methods, while Section 4 provides a detailed evaluation of pedestrian crossings in five cities based on pedestrian behavior and their start-up time. Section 5 verifies the obtained results and simulates the values of input parameters, followed by concluding remarks.

## 2 Literature Rreview

There are many research papers that have specifically addressed pedestrians and their safety. When it comes to signalized pedestrian crossings, the focus has mostly been on the time it takes for pedestrians to cross the pedestrian crossing, but few have paid attention to the pedestrian start-up time, which is equally important and should be considered when allocating green time.

Knoblauch et al. [2]conducted a study in which they collected data to assess pedestrian walking speeds and pedestrian start-up times in relation to location and environmental factors. In their research, they considered the influence of elements such as age, gender, pedestrian speed, street width, type of pedestrian crossing, signal cycle length, curb height, etc. Data were collected during week days over an eight-hour period. Jaiatilake et al. [3] conducted a series of field studies to assess pedestrian start-up times, taking into account factors such as age, gender, group size, and pedestrians' familiarity with signal phases. They found that these factors significantly influenced the start-up time, and they also demonstrated a significant difference in their familiarity with signal phases, although they only considered one signal configuration. Golani and Damti [4] examined group pedestrian behavior, considering age, gender, group size and pedestrians' familiarity with signal phases, aiming to establish a model for estimating the late pedestrian start-up times at signalized pedestrian crossings. Easa and Cheng [5] collected data to establish the correlation coefficient between start-up time and pedestrian speed, presenting a probability method for calculating minimum green time in their paper. Virkler [6] considered several aspects of signal timing in his research, but the greatest attention was focused on the total start-up time for pedestrian platoons. For this reason, the obtained delay (or start-up) times do not provide any insight into individual pedestrian behavior. Ma et al. [7] conducted a study to examine the impact of countdown displays on pedestrian behavior. In the research, pedestrians were classified into two age groups for observation and data were collected during peak pedestrian volumes over three work days per week. Video recording systems were installed at several pedestrian crossings to collect data on pedestrian behavior at crosswalks. Kong and Chua [8] conducted research on pedestrian start-ups in controlled laboratory conditions, categorizing participants into four pedestrian groups: unburdened pedestrians, pedestrians carrying two bags, pedestrians with shopping carts, and pedestrians with strollers. Gillette et al. [9] aimed to determine pedestrian start-up time and behavior when crossing pedestrian crossings depending on wait times, distractions, and types of crossing groups. The study considered differences between genders, age categories, and location characteristics to account for variability in results.

## 3 Methods

### 3.1 MEREC Method

This method serves to objectively determine the quantitative significance of criteria, and consists of the steps listed below [10].

Step 1: Construct the decision matrix.

$$X = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{nj} & \dots & x_{nm} \end{bmatrix} \tag{1}$$

Step 2: Conduct the normalization procedure $n_{ij}^x$ conditioned by the type of criteria B - set of beneficial criteria and C - set of cost criteria.

$$n_{ij}^x = \begin{cases} \frac{\min_k x_{kj}}{x_{ij}} & \text{if} \quad j \in B \\ \frac{x_{ij}}{\max_k x_{kj}} & \text{if} \quad j \in C \end{cases} \tag{2}$$

Step 3: Calculate the overall performance of the alternatives ($S_i$).

$$S_i = \ln\left(1 + \left(\frac{1}{m}\sum_j \left|\ln\left(n_{ij}^x\right)\right|\right)\right) \tag{3}$$

Step 4: Calculate the performance of the alternatives by removing each criterion.

$$S'_{ij} = \ln\left(1 + \left(\frac{1}{m}\sum_{k,k\neq j} \left|\ln\left(n_{ik}^x\right)\right|\right)\right) \tag{4}$$

Step 5: Compute the summation of absolute deviations $E_i$:

$$E_j = \sum_i \left|S'_{ij} - S_i\right| \tag{5}$$

Step 6: Determine the final weights of the criteria $w_i$:

$$W_j = \frac{E_j}{\sum_k E_k} \tag{6}$$

### 3.2 MARCOS Methods

The MARCOS method created by Stević et al. [11] consists of the steps shown in Figure 1.
The following steps are part of the MARCOS method as shown in Figure 1.

$$X = \begin{matrix} & C_1 & C_2 & \dots & C_n \\ AAI & x_{aa1} & x_{aa2} & \dots & x_{aan} \\ A_1 & x_{11} & x_{12} & \dots & x_{1n} \\ A_2 & x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ A_m & x_{m1} & x_{22} & \dots & x_{mn} \\ AI & x_{ai1} & x_{ai2} & \dots & x_{ain} \end{matrix} \tag{7}$$

$$AAI = \min_i x_{ij} \quad \text{if } j \in B \quad \text{and} \quad \max_i x_{ij} \quad \text{if } j \in C \tag{8}$$

$$AI = \max_i x_{ij} \quad \text{if } j \in B \quad \text{and} \quad \min_i x_{ij} \quad \text{if } j \in C \tag{9}$$

$$n_{ij} = \frac{x_{ai}}{x_{ij}} \quad \text{if } j \in C \tag{10}$$

$$n_{ij} = \frac{x_{ij}}{x_{ai}} \quad \text{if } j \in B \tag{11}$$

$$v_{ij} = n_{ij} \times w_j \tag{12}$$

$$K_i^- = \frac{S_i}{S_{aai}} \tag{13}$$

$$K_i^+ = \frac{S_i}{S_{ai}} \tag{14}$$

$$S_i = \sum_{i=1}^{n} v_{ij} \tag{15}$$

$$f\left(K_i^-\right) = \frac{K_i^+}{K_i^+ + K_i^-} \tag{16}$$

$$f\left(K_i^+\right) = \frac{K_i^-}{K_i^+ + K_i^-} \tag{17}$$

$$f\left(K_i\right) = \frac{K_i^+ + K_i^-}{1 + \frac{1-f\left(K_i^+\right)}{f\left(K_i^+\right)} + \frac{1-f\left(K_i^-\right)}{f\left(K_i^-\right)}} \tag{18}$$

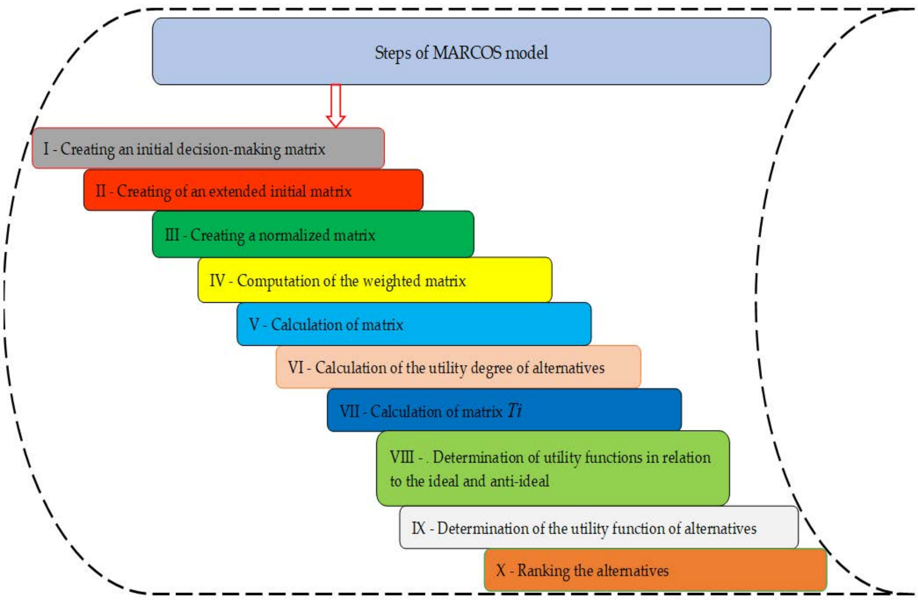


**Figure 1.** Description of MARCOS method

## 4 City Evaluation Model Based on the Concept of Pedestrian Behavior

In this section of the paper, the integrated MEREC-MARCOS model was applied to five cities (four in Bosnia and Herzegovina and one in Serbia), which were evaluated based on pedestrian start-up time when crossing pedestrian crossings. Signalized traffic intersections without counters were considered. From the total sample of approximately 10,000 pedestrians, those related to the mentioned types of intersections were selected. It is important to note that the start-up times for pedestrian crossings are provided in the form of the 85th percentile. Table 1 shows the data processed for the cities of Banja Luka (BL), Novi Sad (NS), Bijeljina (BN), Doboj (DO), and Sarajevo (SA).

**Table 1.** Start-up times representing the initial matrix

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| BL | 4.61 | 4.23 | 3.83 | 4.51 |
| NS | 3.11 | 3.1 | 3 | 2.76 |
| BN | 4.18 | 3.02 | 3.26 | 3.15 |
| DO | 2.87 | 2.87 | 3.21 | 3 |
| SA | 2.87 | 2.85 | 2.71 | 3.63 |

The four criteria considered for evaluating and ranking cities are based on pedestrian age groups, as follows: C1:$< 18$ years, C2:19-40, C3:41-65, and C4:$> 65$. It is also important to note that this model includes both genders, while it is also possible to perform their segmentation.

Applying the second step of the MEREC method, normalization was performed, as shown in Table 2.

**Table 2.** The normalized matrix of the MEREC method

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| BL | 1 | 1 | 1 | 1 |
| NS | 0.674 | 0.733 | 0.785 | 0.612 |
| BN | 0.906 | 0.713 | 0.851 | 0.698 |
| DO | 0.622 | 0.677 | 0.838 | 0.665 |
| SA | 0.623 | 0.674 | 0.708 | 0.804 |

Since it concerns the time it takes for a pedestrian to step onto the pedestrian crossing, their values tend towards minimal values or towards zero in ideal conditions. Therefore, the orientation of the criteria is minimum, i.e., they belong to the cost group.

The next step involves the calculation of the total effect of alternatives $S_i$.

$S_1 = 0.000$; $S_2 = 0.307$; $S_3 = 0.215$; $S_4 = 0.309$; $S_5 = 0.306$

In the 4th step, the effect of alternatives was calculated by removing each criterion $S'_{ij}$ (Table 3).

**Table 3.** Effect of alternatives by removing each criterion $S'_{ij}$

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| BL | 0 | 0 | 0 | 0 |
| NS | 0.16 | 0.172 | 0.182 | 0.147 |
| BN | 0.134 | 0.098 | 0.125 | 0.095 |
| DO | 0.15 | 0.163 | 0.192 | 0.16 |
| SA | 0.148 | 0.159 | 0.166 | 0.184 |

Then, the sum of absolute deviations $E_j$ and criterion weight $w_j$ were calculated (Table 4).

**Table 4.** Values of $E_j$ and weights of criteria $w_j$

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| $E_j$ | 0.544 | 0.544 | 0.472 | 0.551 |
| $w_j$ | 0.258 | 0.258 | 0.223 | 0.261 |

Since the criterion values have been determined, we proceed to evaluate the alternative solutions using the MARCOS method. The initial matrix has already been presented in the paper through the MEREC method, so Table 5 provides the extended initial matrix defined throughout the second step of the MARCOS method.

**Table 5.** Extended initial matrix of MARCOS method

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| AAI | 4.61 | 4.23 | 3.83 | 4.51 |
| BL | 4.61 | 4.23 | 3.83 | 4.51 |
| NS | 3.11 | 3.1 | 3 | 2.76 |
| BN | 4.18 | 3.02 | 3.26 | 3.15 |
| DO | 2.87 | 2.87 | 3.21 | 3 |
| SA | 2.87 | 2.85 | 2.71 | 3.63 |

The third step is the normalization of the previously calculated matrix. The obtained values are shown in Table 6, while the weighted matrix is presented in Table 7.

**Table 6.** Normalized extended initial matrix

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| AAI | 0.622 | 0.674 | 0.708 | 0.612 |
| BL | 0.622 | 0.674 | 0.708 | 0.612 |
| NS | 0.922 | 0.919 | 0.902 | 1 |
| BN | 0.686 | 0.945 | 0.832 | 0.876 |
| DO | 1 | 0.995 | 0.844 | 0.919 |
| SA | 0.999 | 1 | 1 | 0.761 |
| AI | 1 | 1 | 1 | 1 |

**Table 7.** Weighted matrix

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| AAI | 0.106 | 0.095 | 0.104 | 0.106 |
| BL | 0.153 | 0.146 | 0.149 | 0.16 |
| NS | 0.151 | 0.139 | 0.154 | 0.162 |
| BN | 0.121 | 0.096 | 0.124 | 0.113 |
| DO | 0.123 | 0.105 | 0.113 | 0.122 |
| SA | 0.126 | 0.101 | 0.121 | 0.118 |

The final values obtained using the steps of MARCOS method are shown in Table 8.

**Table 8.** Results of applying the MARCOS method

| | $S_i$ | $Ki-$ | $Ki+$ | $f(K_1^-)$ | $f(K_1^+)$ | $f(K_i)$ | **Rank** |
|---|---|---|---|---|---|---|---|
| AAI | 0.652 | 1.000 | | | | | |
| BL | 0.652 | 1.000 | 0.652 | 0.395 | 0.605 | 0.518 | 5 |
| NS | 0.937 | 1.438 | 0.937 | 0.395 | 0.605 | 0.745 | 3 |
| BN | 0.835 | 1.281 | 0.835 | 0.395 | 0.605 | 0.664 | 4 |
| DO | 0.943 | 1.447 | 0.943 | 0.395 | 0.605 | 0.75 | 1 |
| SA | 0.937 | 1.438 | 0.937 | 0.395 | 0.605 | 0.745 | 2 |
| AI | 1.000 | | 1.000 | | | | |

## 5 Discussion with Verification Tests

### 5.1 Sensitivity Analysis

Criteria as influential factors in MCDM models represent an important aspect of the study, especially when we encounter situations where two or more alternative solutions are very close in terms of final values. In this section of the paper, a simulation of new criterion weights was performed across the interval of 5-95% reduction in significance within 40 scenarios. The new simulated values are shown in Figure 2.

After defining the new values, 40 new sensitivity analysis models were created, which are shown in Figure 3.

Considering the initial results, where it is clear that there are nuances among the three best-rated cities, it is understandable why we have come to the conclusion that the model is sensitive to input parameters. This is primarily due to the fact that, depending on the scenario, the top three cities alternate, while BL and BN consistently show the worst characteristics, regardless of the weight of any criterion. The city of Doboj remains in first place only in S23–S30 when the value of the third criterion, which denotes the age group of 41–65 years, drastically decreases because this age group shows the best performance in the city of Sarajevo, which is in second place in the initial result. In scenarios S1–S17, S21–S22, and S31–S40, Sarajevo represents the city with the best performance. In scenarios S18–S20, when the importance of the second criterion relating to the age group of 19–40 drastically decreases, Novi Sad shows the best characteristics because the value of the fourth criterion significantly increases, indicating its superiority compared to other cities.

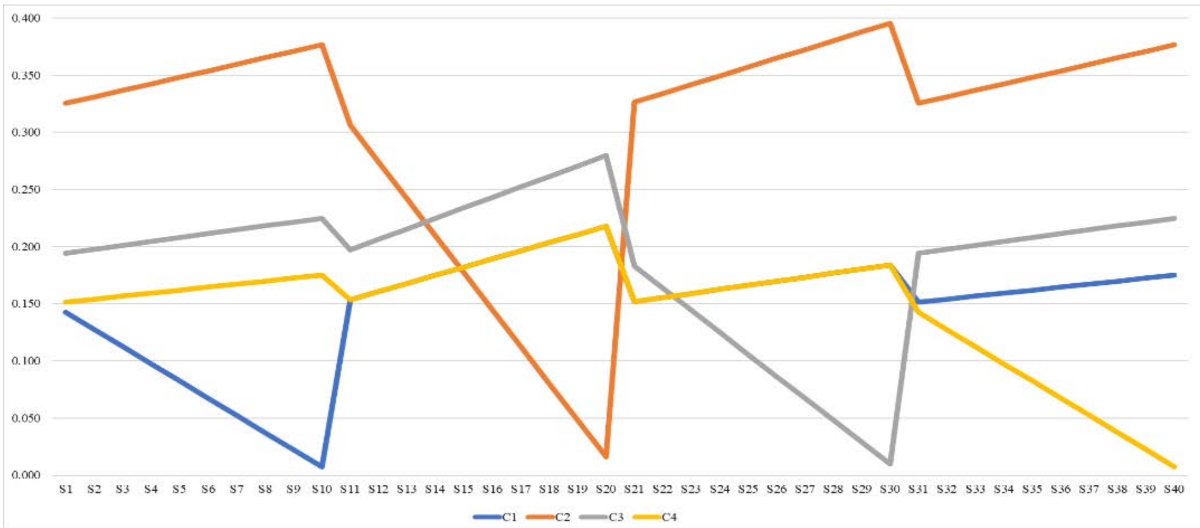


**Figure 2.** Criterion values in 40 scenarios

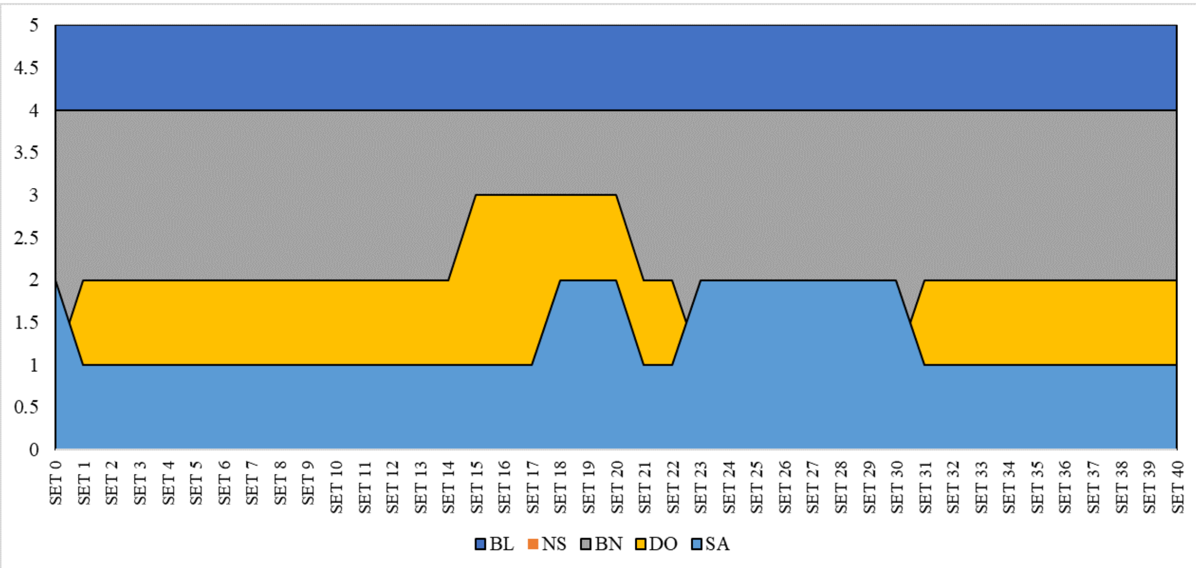


**Figure 3.** Ranks in sensitivity analysis

In addition to the described sensitivity analysis, a comparative analysis (Figure 4) was also conducted with six other methods SAW [12], WASPAS [13], AROMAN [14], EDAS [15], MABAC [16] and CRADIS [17].

Through comparative analysis, it can be concluded that the sensitivity analysis is confirmed because the top three cities change their positions depending on the applied method and normalization procedure.

Based on observations of five signalized crossings without counters, it seems that pedestrians behave differently at the locations where the research was conducted, and that start-up time varies among different age groups.

## 6 Conclusions

Summarizing the results of this research, it can be concluded that pedestrian start-up time is of paramount importance in increasing pedestrian safety when crossing signalized pedestrian crossings.

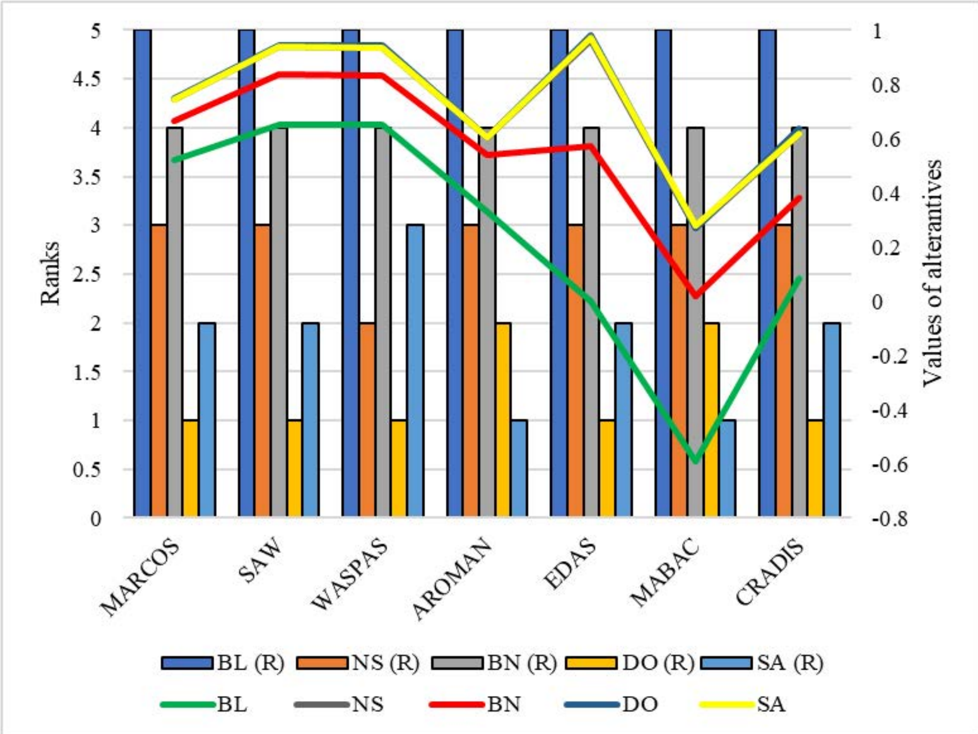


**Figure 4.** Results of comparison with other MCDM methods

For this research, five cities with a total of five four-legged signalized intersections where pedestrians were observed at pedestrian crossings without counters were selected. Only pedestrians positioned in the first line next to the roadway were considered, with a total sample size of approximately 10,000 pedestrians. Pedestrians were divided into four age groups and evaluated from worse to better based on the values obtained. In this paper, a simulation of new criterion weights was performed across the interval of 5–95% reduction in significance within 40 scenarios. Considering the initial results, where it is clear that there are nuances among the three best-rated cities, it is understandable why we conclude that the model is sensitive to input parameters. This is primarily due to the fact that, depending on the scenario, the worst characteristics are consistently shown regardless of the weight of any criterion. Research on pedestrian behavior at five intersections without counters showed that pedestrians behave differently at the locations where the research was conducted and that the start-up time varies among different age groups.

Unfortunately, pedestrian signal design often does not pay enough attention to pedestrian start-up time, which is a relevant factor affecting traffic flows. The design of pedestrian phases is usually based solely on crossing duration, i.e., pedestrian speed, although this can lead to reduced pedestrian safety, i.e., unwanted vehicle-pedestrian conflict situations.

Considering that pedestrians are the most vulnerable and least protected participants in traffic, it is of utmost importance to minimize such situations, which can be achieved by paying more attention to pedestrian start-up time. Additionally, considering both early start-up and delayed time would further increase pedestrian safety.

## Informed Consent Statement

Not applicable.

## Data Availability

The data supporting our research results are included within the article or supplementary material.

## Conflicts of Interest

The authors declare no conflict of interest.

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