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ASSESSMENT OF THE IMPACT OF TRAFFIC SIGNALIZATION ON THE BEHAVIOR OF VULNERABLE ROAD USERS

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Abstract

Pedestrians and cyclists are among the most vulnerable road users, making their safety a central concern in modern and sustainable traffic planning. Particularly critical points in the traffic system are pedestrian crossings, where pedestrians' reaction speed and level of awareness directly influence the level of risk. These locations further highlight the vulnerability of specific subgroups – children, the elderly, and persons with disabilities – who, due to cognitive and physical limitations, have a reduced capacity to assess and respond to traffic situations promptly. To analyze the behavior of vulnerable groups at critical intersection points, a study was conducted at the intersection of St. Roko Street and J. J. Strossmayer Street in Osijek. The intersection is located in the central urban area, characterized by high traffic volumes and relatively long pedestrian crossings. The study was carried out in two phases: the first in April 2024, when the intersection operated without traffic signals, and the second in January 2026, following its reconstruction into a signalized intersection. Data was collected through video analysis of traffic flows during peak hours, with particular emphasis on determining differences in pedestrian movement patterns, levels of attention, and compliance with traffic rules under different traffic management conditions. The study also evaluated the impact of signalization on the behavior of vulnerable road users. The results indicate that signalization of pedestrian crossings contributes to a reduction in certain risky behaviors, while at the same time reducing pedestrians' situational awareness. These findings underscore the importance of careful planning of traffic infrastructure that accounts for the specific needs of children, the elderly, and people with disabilities. In conclusion, enhancing the safety of vulnerable road users requires a combination of infrastructural, technological, and educational measures to systematically reduce risk and improve the overall safety of the traffic system.

Keywords: vulnerable road users, traffic safety, signalized intersection, unsignalized intersection, pedestrian crossings

1 Introduction

Pedestrian safety is one of the fundamental road safety issues in the European Union and represents a significant public health and social challenge. Despite continuous improvements in transport infrastructure and legislation, pedestrians continue to be involved in a significant proportion of serious road accidents, and according to the latest data from the European Commission, they account for approximately 18% of all road fatalities [1]. Vulnerable road users include not only pedestrians but also cyclists, with particularly vulnerable subgroups being children, the elderly, and people with disabilities.

These groups often have limited cognitive abilities, perceptual speed, motor skills, and physical mobility, which increase their exposure to risk [2]. Older adults account for a significant proportion of pedestrian fatalities, which is associated with increased physical vulnerability and slower reaction times [3-6]. At the same time, younger age groups are more likely to engage in risky traffic behavior. An additional challenge is the increasing use of mobile and other electronic devices while moving, which can reduce the level of situational awareness and increase the likelihood of conflict situations with vehicles [3, 7]. Critical points in traffic systems are intersections in urban areas, especially pedestrian crossings [8]. Intersections with marked pedestrian crossings have a high number of potential conflict points between vehicles and pedestrians, and the number of conflict points increases with the number of traffic lanes and pedestrian crossings at the intersection approaches. The implementation of traffic signalization is one of the most common measures used to enhance safety; however, its actual impact on the behavior of vulnerable road users requires detailed analysis. The aim of this study is to assess the impact of traffic signalization on the behavior of vulnerable road users by comparing relevant indicators before and after the introduction of traffic lights.

2 Methodology

2.1 Observation location

For the purpose of analyzing the behavior of vulnerable groups at critical points of intersections, i.e., at marked pedestrian crossings, a study was conducted at the intersection of St. Roko Street and J. J. Strossmayer Street in Osijek. The intersection in question is a T-intersection located in the central urban area, with significant traffic volumes and relatively long pedestrian crossings. The intersection carries two-way mixed traffic flow, with J. J. Strossmayer Street having a total of four traffic lanes and tram operations, while St. Roko Street has two traffic lanes. The maximum allowed vehicle speed in the intersection zone is regulated by traffic signs and is 50 km/h. Sidewalks are present on both sides of the intersection, and a pedestrian crossing is marked on each approach. Two pedestrian crossings on J.J. Strossmayer Street have a length of 12.0 m, and one on St. Roko Street has a length of 9.5 m. The intersection is located in close proximity to tram stops, a religious building, an educational center, and other facilities that attract significant pedestrian and vehicular traffic. The study was conducted in two phases. The first phase took place in April 2024, when the intersection was unsignalized, and the second phase in January 2026, after the intersection was reconstructed as signalized. Data were collected through video analysis of traffic flows during peak hours.

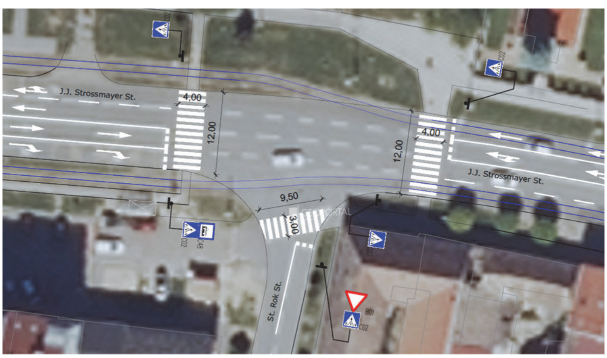

Figure 1 Unsignalized intersection, 2024

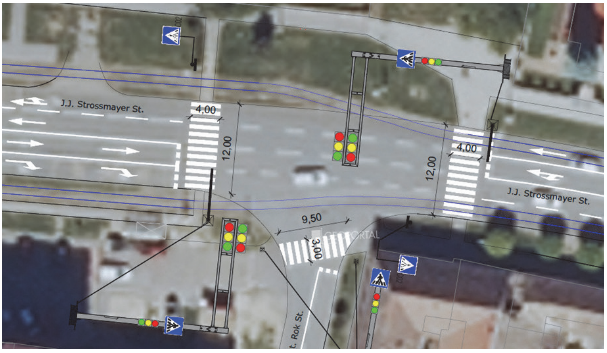

Figure 2 Signalized intersection, 2026

2.2 Selection of influential parameters

To capture the majority of behaviors of the observed groups, each pedestrian crossing was observed during a weekday in the morning (7:30–8:30) and afternoon (14:30–15:30). Observations were conducted in April 2024 (phase 1) and January 2026 (phase 2). During the study, a total of 160 pedestrian and cyclist crossings were recorded, with the following aspects observed: type of participant/mode of movement – pedestrians, cyclists, and scooter riders; characteristics of the observed groups – age, gender, and mobility limitations; risky behaviors – spatial violations, technological distractions, and situational awareness – measured as reaction time. Participants were initially classified into five age groups: children and teenagers (4–18 years), young adults (19–24 years), adults (25–40 years), middle-aged adults (41–65 years), and older adults (› 65 years). For further analysis, these groups were combined into three broader categories: children and teenagers as group AG1, people aged 19 to 65 as group AG2, and older adults as group AG3. This categorization was applied with regard to the most vulnerable road users – AG1 and AG3, while AG2 group served as a reference group for comparison purposes.
Spatial violations at unsignalized intersections were defined as movements outside the marked pedestrian crossing and running across the pedestrian crossing. At signalized intersections, in addition to these behaviors, crossing during the pedestrian red signal was considered a separate violation. Additionally, technological distractions were analyzed, including mobile phone use while crossing, such as typing messages, browsing content, or engaging in phone calls. Situational awareness was assessed exclusively through reaction time, defined as the time taken by a participant to visually verify approaching traffic by looking left and right before stepping onto the roadway. In addition to the behavior of the observed groups, the analysis also included the infrastructural characteristics of the location, primarily the lengths of pedestrian crossings. These parameters were used to calculate the time spent in the conflict zone and the average movement speed of individual groups. The time spent in the conflict zone was defined as the time from the first step onto the roadway until the first step onto the sidewalk.

3 Analysis of results

3.1 Unsignalized intersection

Based on the analysis of video recordings of the unsignalized intersection, a database was created containing 74 recorded crossings. In the structure of the observed vulnerable road users, pedestrians accounted for 68.92%, cyclists 28.38%, and electric scooter users 2.70%.

Among pedestrians, 35.30% belonged to the group of children and teenagers, 52.94% to the group of young, adult, and middle-aged persons, while 11.76% belonged to the older age group. In the structure of cyclists, children and teenagers predominated (47.62%), followed by young and middle-aged persons (38.10%), while 14.29% belonged to the older age group. All scooter users belonged to the age group of children and teenagers. Within the group of child pedestrians, 66.67% were girls and 33.34% were boys, with 9.81% of child pedestrians crossing the pedestrian crossing accompanied by an adult. Reduced mobility was recorded exclusively among pedestrians in the older age group, i.e. pedestrians over 65 years of age.
The analysis of risky behavior at unsignalized pedestrian crossings showed that approximately 10% of pedestrians used a mobile phone while crossing. Spatial violations, in the sense of moving outside the marked pedestrian crossing, were recorded in 8% of pedestrians, while among cyclists this share was significantly higher, reaching as much as 38%. Running across the pedestrian crossing was recorded in 8% of pedestrians. Furthermore, it was recorded that no cyclist or scooter user used protective equipment, and as many as 90% of cyclists did not adjust their mode of movement before crossing, while scooter users in 100% of cases did not stop and adjust their movement before crossing.
Reaction time, defined as the visual check of approaching traffic before stepping onto the roadway, showed that 51% of pedestrians checked at least one direction, while 49% of pedestrians did not perform any traffic check. Among pedestrians who did not perform a traffic check, 16.3% were children and 8.2% were persons older than 65 years. Among cyclists, 76% of participants entered the roadway without first checking for approaching traffic. The longest reaction time among pedestrians was recorded in children and amounted to 2.83 s, while the shortest reaction time was recorded in young, adult, and middle-aged pedestrians and amounted to 0.73 s. Cyclists in all age groups showed a significantly lower level of checking approaching traffic compared to pedestrians; the longest reaction time was 2.24 s among middle-aged cyclists, while the shortest reaction time of 0.5 s was recorded among cyclists in the younger age group. The lowest movement speeds in the conflict zone were recorded among elderly pedestrians. Thus, at a pedestrian crossing with a length of 12 m, the average speed of elderly pedestrians was 1.40 m/s, which corresponds to an average crossing time of 8.7 s. In cases of reduced mobility, for example when using a cane, the average speed decreased to approximately 1.0 m/s. The highest pedestrian speed at the same pedestrian crossing was recorded among middle-aged pedestrians and amounted to 2.3 m/s. At the pedestrian crossing in St. Roko Street, the lowest movement speed (0.97 m/s) was recorded among participants aged 15 to 18, while the average speed of children was 1.5 m/s. The highest recorded speed (3.22 m/s) was observed in a middle-aged person, while the average speed of older persons at that location was 1.30 m/s.

3.2 Signalized intersection

Based on the processing of video recordings of the observed signalized intersection, a database was created containing 86 crossings. In the structure of observed participants, pedestrians dominated (82.56%), followed by cyclists (16.28%), while scooter users accounted for 1.16% of the total sample. At the signalized intersection, within the group of pedestrians, 36.62% were children and teenagers, 53.52% were young, adult, and middle-aged participants, while 9.86% were elderly. Among cyclists, the age structure was significantly different: 7.14% were children and teenagers, 71.43% were young, adult, and middle-aged participants, and 21.43% were elderly persons. In all recorded cases, electric scooter users belonged to the group of children and teenagers. Within the group of child pedestrians, 73% were girls and 27% were boys. A total of 5.6% of children crossed accompanied by an adult. Reduced mobility was recorded exclusively among pedestrians older than 65 years.

Among the risky behaviors of pedestrians at signalized pedestrian crossings, it was found that approximately 6% of pedestrians used a mobile phone while crossing. Spatial violations, i.e. crossing outside the marked pedestrian crossing, were recorded in 4% of pedestrians, while among cyclists this share was significantly higher and amounted to 29%. Running across the pedestrian crossing was recorded in 1.4% of pedestrians. During observation, not a single cyclist or scooter user was recorded wearing protective equipment. Furthermore, 79% of cyclists did not adjust their mode of movement while crossing the pedestrian crossing, while scooter users in 100% of cases did not stop and adjust their movement at the pedestrian crossing. Non-compliance with the red pedestrian signal was recorded in 3% of pedestrians and as many as 15% of cyclists.
The analysis of reaction time included the behavior of pedestrians and cyclists after the pedestrian signal turned green, with emphasis on whether they verified that it was safe to cross, i.e. whether they checked for approaching traffic. Within the pedestrian group, 21% of participants checked traffic in at least one direction, while 79% did not look either left or right before stepping onto the roadway. Among pedestrians who did not perform a traffic check, 7.6% were children and 3.8% were persons older than 65 years. Among cyclists, 79% of participants also omitted checking the traffic situation before crossing. The longest reaction time was recorded among child pedestrians and amounted to 2.13 s, while the shortest average reaction time was recorded among younger, adult, and middle-aged pedestrians and amounted to 0.83 s. Cyclists showed significantly less checking of approaching traffic compared to pedestrians, with the longest reaction time amounting to 1.89 s among older cyclists, and the shortest reaction time of 1.0 s among middle-aged cyclists. Elderly pedestrians were recorded with the lowest average movement speed in the conflict zone. At a pedestrian crossing with a length of 12 m, the average speed was 1.15 m/s, corresponding to an average crossing time of 10.36 s. In cases of reduced mobility, for example with the help of a cane, the average speed decreased to 0.68 m/s. The highest movement speed at the same pedestrian crossing was recorded among middle-aged pedestrians and amounted to 2.6 m/s. At the pedestrian crossing in St. Roko Street, the lowest movement speed (0.90 m/s) was recorded among elderly pedestrians, while the average speed of this group was 1.0 m/s. The highest recorded movement speed at that location was 2.3 m/s and was observed in middle-aged pedestrians.

4 Comparison of results

The analysis of data collected at unsignalized and signalized intersections enabled a detailed comparison of the behavior of vulnerable road users. The introduction of traffic signals resulted in a reduction in most risky behaviors among pedestrians and cyclists. The share of pedestrians using a mobile phone while crossing decreased from approximately 10% to 6%, spatial violations decreased from 8% to 4%, while running across the pedestrian crossing decreased from 8% to 1.4%. Although to a lesser extent than among pedestrians, a positive effect was also recorded among cyclists. Spatial violations decreased from 38% to 28%, and the share of cyclists crossing the pedestrian crossing without first dismounting decreased from 90% to 79%. Despite the positive impact of signalization on regulating risky behavior, a decline in situational awareness was simultaneously recorded. At the unsignalized intersection, 51% of pedestrians performed a visual check of approaching traffic before crossing, while at the signalized intersection this share was only 21%. These results indicate a pronounced reliance of participants on the signaling system. With regard to reaction time, at the unsignalized intersection the longest average reaction time was recorded among child pedestrians (AG1) and amounted to 2.16 s, while at the signalized intersection a significantly shorter reaction time (1.4 s) was recorded in the same age group. All observed age groups had shorter reaction times at the signalized intersection compared to the unsignalized one.

The observed difference may be attributed to the fact that at the signalized intersection pedestrians begin crossing under controlled conditions, where the signal and stopped vehicle traffic provide a greater sense of safety. Such conditions reduce the need for additional assessment of the traffic situation, resulting in shorter reaction times but also a lower level of situational awareness. A comparison of reaction times by age groups (AG1–AG3) in both phases of the study is shown in figure 3.

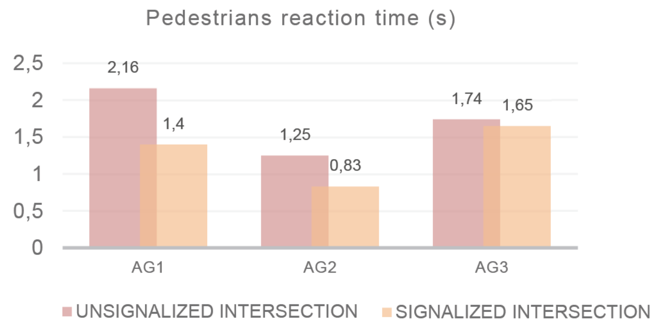

Figure 3 Comparison of reaction times at the unsignalized and signalized intersections

The results of the movement speed analysis showed that the lowest average crossing speed was recorded among elderly persons (AG3) in both phases of the study. At the pedestrian crossing with a length of 12.0 m, it was determined that pedestrians achieved higher average speeds at the unsignalized crossing compared to the signalized one. Conversely, at the shorter pedestrian crossing with a length of 9.50 m, in most cases higher speeds were recorded after the introduction of traffic signals. A comparison of the average pedestrian speeds according to intersection and pedestrian age group is shown in figure 4.

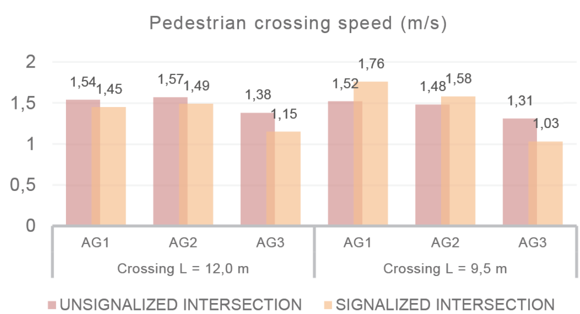

Figure 4 Comparison of average pedestrian speeds according to intersection type and pedestrian age group

5 Conclusion

The results of this study confirm that signalization significantly contributes to increased traffic discipline among vulnerable road users, but it does not eliminate all forms of risk. The recorded reduction in risky behaviors, such as mobile phone use, spatial violations, and running across the pedestrian crossing, indicates a positive effect of the infrastructural intervention. However, at the same time, a decline in situational awareness was recorded, suggesting that pedestrians rely more heavily on the signaling system and assess the traffic situation less before crossing.

This is consistent with research conducted in Baltimore [7], which indicates that the presence of traffic signals may lead to more passive behavior and reliance on visual signals instead of one's own risk assessment. The analysis of reaction time and movement speed showed significant differences between age groups. Children (AG1) and elderly persons (AG3) had longer reaction times and lower average crossing speeds, confirming earlier studies on the greater vulnerability of these groups in traffic [3]. These results emphasize the need to adapt traffic infrastructure to the actual abilities of users, for example by extending the duration of the pedestrian green phase at signalized intersections and by implementing physical elements such as pedestrian refuge islands for safe waiting, which is also recommended in relevant studies [5, 8–9]. Cyclists showed a high degree of non-compliance with traffic rules in both phases of the study, including crossing without dismounting and disregarding the red signal. These results indicate the need for targeted cyclist education and increased supervision at critical points.

In conclusion, signalization of intersections represents an effective measure for improving traffic discipline and reducing risky behaviors, but its effect is partial. The safety of pedestrians and cyclists at urban intersections requires a holistic approach that combines adapted infrastructure, education, technological systems, and the promotion of conscious behavior in traffic. Special attention must be paid to the most vulnerable groups – children and the elderly – whose physical and cognitive abilities require additional measures in the planning and implementation of traffic measures.

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