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## **MULTI-CRITERION EVALUATION OF SAFETY AND MOBILITY IMPROVEMENTS IN PEDESTRIAN AND RAIL TRAFFIC FLOW INTERSECTION ZONES: A CASE STUDY FROM ZAGREB, CROATIA**

**Summary.** Level crossings and pedestrian crossings are the only official locations on the railway network where pedestrians are allowed to cross the tracks on the same level. Unauthorized pedestrian movement on railway tracks outside these designated crossings poses significant safety risks, as trespassers can disrupt train operations and cause fatal accidents. This paper focuses on illegal pedestrian crossings over railway tracks, presenting a case study of pedestrian traffic flows in the Vrapče settlement in the western part of Zagreb, Croatia. Based on a comprehensive analysis of existing infrastructure and pedestrian traffic flows, supported by statistical data, on-site observations, and camera recordings of their illegal crossings, new traffic solutions are proposed and evaluated by an analytic hierarchy process (AHP), which is a multi-criteria decision-making method. The results indicate that the selected optimal solution effectively eliminates trespassing while ensuring pedestrian safety and enhancing mobility. Policy implications include the need for integrated urban transport measures that combine infrastructure upgrades with public education, in line with European railway safety directives. The findings underscore the importance of prioritizing pedestrian access improvements and safety interventions in transport planning.

### **1. INTRODUCTION**

Every city has areas where several types of traffic flows intersect. Problems arise at intersections of pedestrian and other traffic flows, particularly at the intersections of pedestrian and railway flows. Pedestrian and railway crossing zones at the same level often represent traffic bottlenecks. Therefore, adequate infrastructure and equipment are required to provide a satisfactory level of safety without disrupting traffic flow. Due to the sometimes poorly constructed or too sparse official crossings over the railway (pedestrian crossings, underpasses, etc.), pedestrians use improvised crossings, although this is not allowed and is dangerous. Such an illicit movement constitutes trespassing.

According to the definition, a trespasser is any person present on railway premises where such presence is forbidden, except for level crossing users [1]. The lack of protective fences along the railway also highlights a problem with pedestrian safety. Pedestrians move near the railway every day, and the daily migration of people creates improvised "trodden" paths, or so-called "wild crossings." With such risky behavior, they endanger their lives every day, but this also affects other traffic participants (e.g., train drivers) and society. Therefore, trespassing on railway tracks is a significant problem that often results in traffic accidents with injuries or fatalities [2].

The International Union of Railways (UIC) developed the "UIC Safety Database" [3], an open database available to all infrastructure managers worldwide, with the primary goal of achieving an

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international harmonization of definitions and perimeters, ensuring that safety data are shared confidentially and are comparable across various countries and regions. Since its inception (2006), 36 companies from 33 countries have contributed [4]. According to the UIC Safety Database, 52.76% of victims on railway tracks were unauthorized persons (data obtained from 2012 to 2023 from 24 railway infrastructure managers). That the most fatalities were unauthorized people on railway premises is confirmed by Eurostat, the official statistics database of the European Union. In 2023, fatalities in the category of “unauthorized persons” remained the largest category of victims, representing 58.4% of all people killed in railway accidents [5].

From 2014 to 2024, 78 trespassers were killed and another 78 were injured on railway tracks in Croatia [6]. Some features of trespassing fatalities during this observation period can be highlighted. The highest number of trespassing fatalities occurred in 2017 (16.7%). The highest proportion of fatalities occurred in November (12.8%), followed by February and May (11.5%). Most of the trespassing fatalities happened on main railway lines (87.2%), and 71.5% of fatality cases were males.

The present study addresses trespassing, specifically illegal pedestrian crossings over railway tracks in pedestrian and railway crossing zones, which affect traffic flows in the Zagreb settlement of Vrapče. The analyzed locations contain infrastructure for safe crossing of railway tracks, but for several reasons, most pedestrians do not use these legal crossings. This research includes detailed analyses of the existing traffic infrastructure, the current state of safety, and traffic flows. Based on the insights gained, new traffic solutions were developed to eliminate current deficiencies and enhance safety and mobility in the observed study area. To evaluate the proposed solutions and select the optimal one, a multi-criteria analysis was performed using the AHP method.

## 2. LITERATURE REVIEW

Trespassing on railways is a global concern, and various preventive measures have been proposed [2, 7-9]. A systematic review of the recent literature highlights several factors influencing the occurrence of trespassing accidents, including the locations of frequent railway trespassing, the temporal frequency of railway trespassing, trespassers' profiles and behaviors, motivation for and general knowledge of railway trespassing, and other factors and models for railway trespassing accidents [2]. The findings underscore the multifaceted nature of trespassing and the importance of integrating behavioral, environmental, and infrastructural perspectives when analyzing risk.

Technological systems for real-time detection have been developed to enhance the understanding of *where*, *when*, and *how* trespassing occurs. These include advanced video analytics platforms and obstacle-detection systems that leverage AI-enabled image processing and CCTV monitoring to identify human intrusions along railway rights-of-way [10-11]. However, researchers have emphasized that trespass risk is highly context-dependent and varies according to local conditions such as urban density, time of day, land-use patterns, and sociocultural norms; therefore, interventions must be tailored to specific environments rather than uniform across all contexts [2, 9].

In addition to spatial and technological analyses, several studies have examined the attitudes and behaviors of particular groups of trespassers. Research involving residents living near railway lines investigated the factors shaping individuals' decisions to use or avoid illegal shortcuts, ultimately aiming to inform targeted preventive measures [12]. Complementary work focusing on children and adolescents identified key considerations for designing educational initiatives for younger populations based on qualitative data collected through school-based focus groups [13]. Education campaigns targeting youth and communities have shown promise, especially when they are repeated [2].

One study [14] proposed optimization measures for accident prevention when rail monitoring is needed by analyzing factors that impact the severity of injuries in railway trespassing accidents from the trespasser's perspective. The multinomial logit model is used to identify the factors and characteristics associated with trespasser injury severity using Federal Railroad Administration accident record data. Although physical countermeasures, such as fencing, locked gates, and enhanced level crossings, are widely implemented, evidence suggests that these measures alone are insufficient to eliminate trespassing and must be complemented by behavioral and community-focused interventions. The EU-

funded RESTRAIL compiled a set of engineering safety measures, combined with community awareness campaigns, to reinforce behavioral change [7-8].

### 3. METHODOLOGY AND DATA

The authors of this research utilized existing data from the railway infrastructure manager on traffic incidents and accident statistics, as well as field-collected data on traffic volume and pedestrian risky behavior. Statistical data on incidents and accidents from 2014 to 2024 are analyzed. The research methodology contains the following steps:

- Analysis of the current situation of the section of the Croatian railway network in the Vrapče settlement (the western part of Zagreb, Croatia):
  - Collecting historical statistical data on traffic accidents, infrastructure data, and traffic flow data from the infrastructure manager and passenger transport carrier, including characteristics of the traffic network, timetable, daily number of trains, statistics of traffic incidents and accidents.
  - Collecting field data: inspection of an existing railway infrastructure, real data about the size and distribution of the current traffic load, analysis of traffic flows, traffic count, number of trespassers, and human behavior.
  - Traffic flows will be analyzed by collecting input data by counting traffic using video recordings. In addition to pedestrians who use the underpass at the eastern location to cross to the other side of the track or legally cross the track, pedestrians who cross the track illegally at both locations, as well as the trains in traffic, will be included. Data collection will be carried out during morning and evening peak hours (7:00–9:00, 19:00–21:00) and off-peak hours (12:00–13:00).
  - Video surveillance: monitoring of trespassers' risky behavior.
- Proposal of new solutions to prevent trespassing and increase safety.
- Multi-criteria analysis of traffic solutions: evaluation of the proposed solutions using the AHP method.

The AHP method developed by Thomas L. Saaty to address complex multicriteria decision-making problems [15-17] is used to evaluate the proposed solutions. The strength of the AHP method is that, as a multicriteria method, it can be easily adapted to different numbers of attributes. This method was chosen for its ability to assess solutions based on multiple criteria. The AHP method is often used to evaluate transport projects [18-22].

### 4. CASE STUDY

#### 4.1. Study area

The analyzed zone is the settlement of Vrapče, which is located in the western part of the city of Zagreb, Croatia. The international double-track railway M101 DG - S. Marof - Zagreb GK passes alongside this area. From a macro-location perspective, the coverage zone extends from the western part, where the Vrapče railway stops and the Vrapče bus terminal is located, to the eastern part of the coverage zone, encompassing Oranice Street. There are two critical locations in this area mentioned, which covers approximately 900 meters. One is located between the Vrapče railway stop and the Vrapče bus terminal, where "wild crossings" occur. Since the area is not designed for pedestrian movement, there is no pedestrian crossing at the intersection of Ilica Street, Majke Terezije Street, and Aleja Bologne Street. At the second critical location, there are "wild crossings" over the Zagreb - Savski Marof railway line between the Vrapčak stream and Oranice Street, which is constructed at grade and passes under Kožinčev Put Street and the Zagreb - Savski Marof railway line (Fig. 1).



Fig. 1. Study area – Macrolocation and microlocations 1 and 2

#### 4.2. Problem

According to the traffic accident statistics database from 2014 to 2024 concerning the analyzed zone, there were nine fatalities and nine injured trespassers during this period [6]. These data exclude accidents and incidents at level crossings. All accidents resulted from risky human behavior.

The existing pedestrian traffic infrastructure is present, but it is not in optimal condition. At both observed locations where illegal crossings occur, there is infrastructure that allows pedestrians to cross the railway at grade safely (i.e., an underpass near each location).

The underpass at the eastern location is a simple underpass in the form of a pedestrian path, levelled and separated from the roadway for vehicle traffic by a fence. It features stairs at entrance/exit number 2, and at the transition from the stairs to the pedestrian path, mirrors are installed to mitigate the risk of collisions with cyclists approaching at high speeds from both sides due to the slope. However, the underpass's capacity is insufficient; the fence and handrails at the entrance/exit are damaged; and there is no ramp or elevator, rendering the underpass inaccessible to cyclists, electric scooters, people with disabilities, individuals with reduced mobility, and individuals with baby strollers (Fig. 2).



Fig. 2. Underpass in the western location

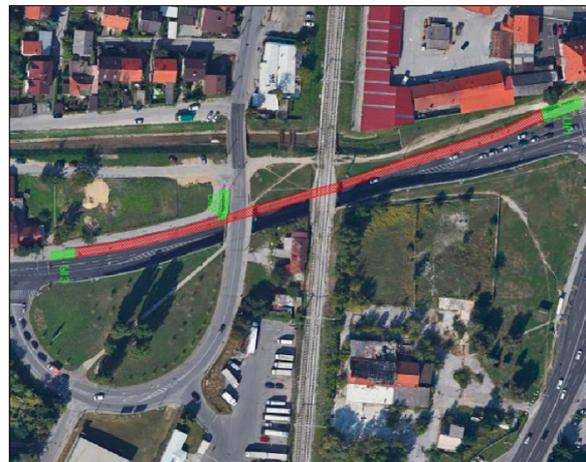


Fig. 3. Underpass in the eastern location

The underpass located near the western site, where illegal crossings occur, is in good condition and has sufficient capacity to meet the pedestrian traffic demand at that location (Fig. 3). However, the underpass lacks night lighting and is marred by extensive graffiti and inscriptions on its walls, causing fear and discomfort for pedestrians using the underpass. Also, the distance from the western location where the illegal crossings occur to the underpass is 250 meters.

## 5. RESULTS

### 5.1. Analysis of traffic flow

Data collected by counting traffic using video recordings show traffic flows at both critical locations (Figs. 4 and 5). Illegal crossings are more prevalent than legal crossings over the railway at the eastern location.

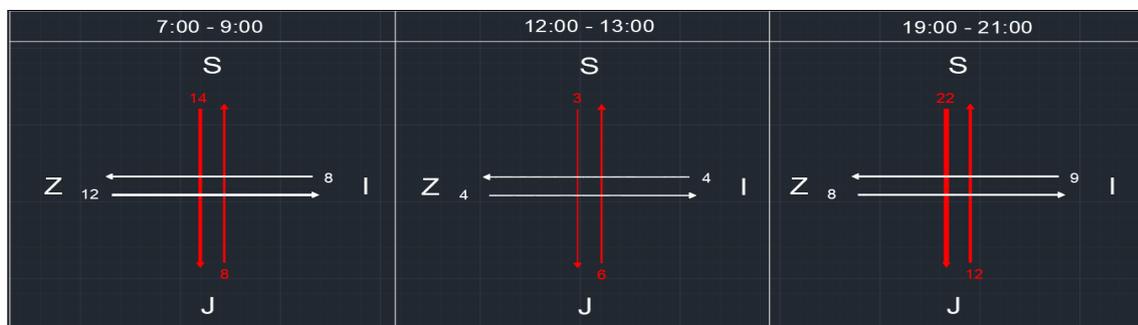


Fig. 4. Traffic load from illegal pedestrian crossings and train traffic at the western location (red: illegal crossings; white: number of trains)

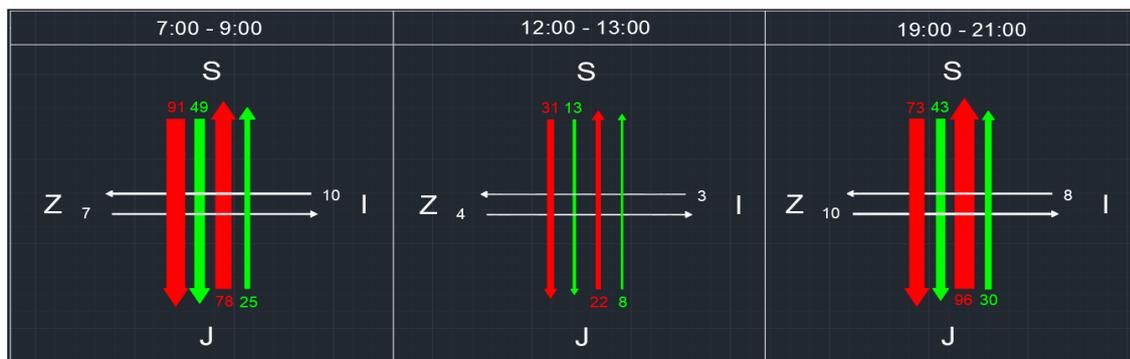


Fig. 5. Traffic load from illegal pedestrian crossings and train traffic at the eastern location (red: illegal crossings; green: legal crossings; white: number of trains)

### 5.2. Proposal of new traffic solutions

The proposals for new traffic solutions consist of three variants, each with a proposed solution for the eastern and western locations where illegal crossings occur. The proposed solutions are illustrated schematically on a digital orthophoto map background, accompanied by textual explanations.

Variant 1 presents proposals for solutions for the eastern and western locations that are simple and the least economically demanding yet effective (Figs. 6 and 7). The proposal for Variant 1 is to install fences at both locations on each side of the track and anti-trespass panels on the track. In the eastern location, the suggested solution is to install a 100-meter-long fence on each side of the location where illegal crossings occur, install anti-trespass panels, and install an elevator at entrance/exit number 2,

which is designed as stairs. In the western location, the fence is being installed from the Vrapče railway station to the east, along a length of 100 meters on each side of the railway, and anti-trespass panels are being installed on the railway along the length of the fence.

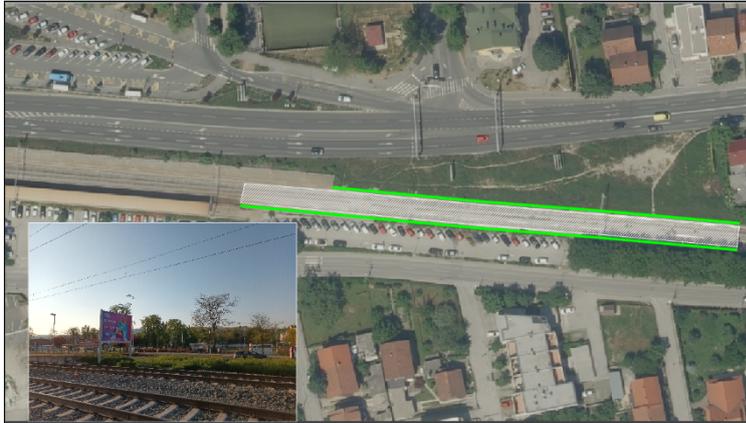


Fig. 6. Variant 1 – west location



Fig. 7. Variant 1 – east location

The proposed solution for Variant 2 at the western location is an upgrade of Variant 1. In addition to the fence and anti-trespass panels, the solution for Variant 2 includes the construction of a short overpass that does not occupy much space. The entrance/exit of the warden on the north side of the railway is connected to the Vrapče railway station, and the entrance/exit of the warden on the south side of the railway is at the parking lot itself (Fig. 8). In addition to the fence and anti-trespass panels, the solution for Variant 2 at the eastern location involves constructing a new underpass with three entrances/exits, along with an elevator at entrance/exit number 2. Due to the length of the underpass, it can be constructed with a slight slope, so no elevators or stairs are needed at entrances/exits 1 and 3, resulting in an acceptable level of accessibility for people with disabilities, those with reduced mobility, those with strollers, cyclists, and electric scooter users. The sufficient width of the underpass allows for the installation of a fence in the middle to separate pedestrian flows (Fig. 9).



Fig. 8. Variant 2 – west location



Fig. 9. Variant 2 – east location

The proposed solution for Variant 3 at the western location includes the construction of an underpass with three entrances and exits (Fig. 10). The underpass would connect the parking lot on the south side of the railway line next to the Vrapče railway station and the Vrapče bus terminal, which is located on the north side of the railway line (i.e., northwest of the location where the illegal crossings occur). Each entrance and exit would be equipped with an elevator to ensure accessibility for people with disabilities, those with reduced mobility, individuals with baby strollers, cyclists, and electric scooter users. The fences and anti-trespass panels from Variant 2 are also present in this variant.

Variant 3 at the eastern location is an upgrade of Variant 2 at the same location. The construction of a new underpass with an addition, namely the conversion of the old or existing underpass into a bicycle path, is proposed. The reason for adding the bicycle path is the significant number of observed cyclists for data collection or traffic counting (Fig. 11).

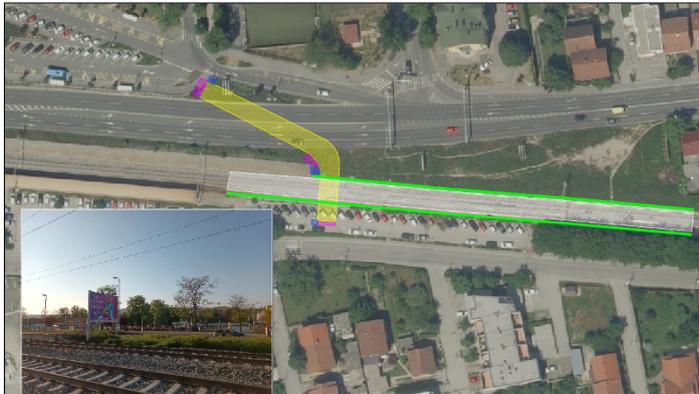


Fig. 10. Variant 3 – west location



Fig. 11. Variant 3 – east location

### 5.3. Evaluation of proposed traffic solutions

The proposed traffic solution variants were evaluated according to the defined criteria and their sub-criteria using the AHP method and the Expert Choice software tool. The evaluation of the proposed variants for a new traffic solution using the AHP method and the software tool Expert Choice is based on the defined criteria and their sub-criteria (Table 1). The variants are explained in detail in Section 3.3. The first variant consists of installing a fence, an anti-trespass panel, and an elevator in the eastern location and installing a fence and an anti-trespass panel in the western location. The second variant is an upgrade to the first one, with the additions being the construction of a new underpass in the eastern location and the construction of an underpass in the western location. The third variant in the east location is an upgrade of Variant 2, which includes the construction of a separate bicycle path. Variant 3 in the western location is an upgrade of Variant 1, which includes an underpass that connects the southern and northern sides of the Vrapče railway stop and extends to the Vrapče bus terminal.

Table 1

Criteria and sub-criteria for the evaluation of the proposed variants

No.	Criteria	Sub-criteria
1	Safety	<ul style="list-style-type: none"> <li>– increasing pedestrian and cyclist safety</li> <li>– spatial separation of pedestrian and railway flows</li> <li>– prevention of access to the railway</li> </ul>
2	Increasing urban mobility	<ul style="list-style-type: none"> <li>– pedestrian flows</li> <li>– cyclist flows</li> <li>– accessibility for people with disabilities</li> </ul>
3	Economic indicators	<ul style="list-style-type: none"> <li>– construction costs</li> <li>– maintenance costs</li> </ul>
4	Spatial and urban planning indicators	<ul style="list-style-type: none"> <li>– additional area occupied</li> <li>– complexity of implementation</li> <li>– impact on the city's skyline</li> </ul>
5	Infrastructure indicators	<ul style="list-style-type: none"> <li>– implementation period</li> <li>– infrastructure lifespan</li> </ul>
6	Social indicators	<ul style="list-style-type: none"> <li>– increasing the attractiveness of the location</li> <li>– increasing the quality of life</li> </ul>

After the hierarchical structure of the AHP model was defined, the weights of the criteria and sub-criteria were determined based on expert assessments and comparisons with case studies involving similar issues [23]. For the pairwise comparisons of the criteria and sub-criteria, judgments were made using a Saaty scale (1–9). The individual judgments were aggregated using the geometric mean, and priorities were calculated using the eigenvector method. Consistency ratios were computed for each comparison matrix to ensure reliability (all values were  $<0.1$ ).

The “safety” criterion is given the highest importance. The increase in safety is directly affected by the spatial separation of railway and pedestrian flows and the inability of pedestrians to access the railway. This paper aims to offer solutions that increase pedestrian safety and mobility. Therefore, the following most crucial criterion is the criterion labeled “increase in urban mobility.” This criterion is reflected by increases in pedestrian and cyclist flows and accessibility for people with disabilities. The “economic indicators” criterion represents indicators in the form of costs, namely, construction costs and maintenance costs. The “spatial and urban indicators” criterion refers to the additional occupation of land, the complexity of the implementation, and the impact on the city's skyline. The critical indicators included in the “infrastructural indicators” criterion are the implementation period (i.e., the time required to implement measures) and the indicator of the service life of the infrastructure. The “social indicators” criterion indicates increases in the attractiveness of the location and the quality of life. Fig. 12 shows the ranked criteria in the Expert Choice software tool. After the criteria and sub-criteria were ranked, the proposed variants were evaluated.

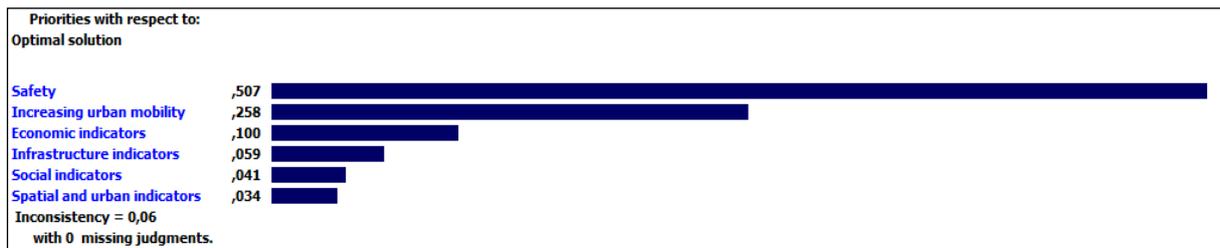


Fig. 12. Importance of criteria (Expert Choice)

According to the multi-criteria analysis of the criteria and their sub-criteria, Variant 3 is the optimal choice (.586), followed by Variant 2 (.240) and Variant 1 (.174), as shown in Fig. 13.

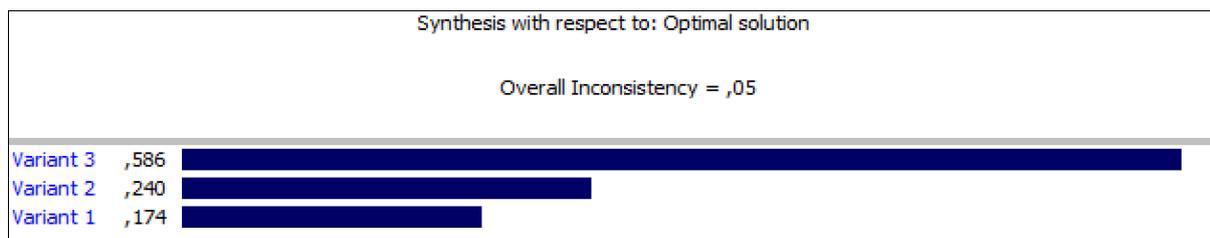


Fig. 13. Ranking of variants (Expert Choice)

A sensitivity analysis was conducted regarding the requirements "spatial-urban indicators" and "increase in urban mobility" to demonstrate the sensitivity of variants to changes in the importance of criteria. In both cases, Variant 3 was optimal. Further sensitivity analysis showed that the optimality of Variant 3 could be affected only by its higher implementation costs compared to the other two variants.

## 6. DISCUSSION

Accidents and incidents involving pedestrians and cyclists are common in rail transport. The risky behavior of road users is a significant concern for road and railway safety. One of the main factors

leading to accidents is human error, which often involves illegal actions or a lack of knowledge of road and rail safety. However, even if risky behavior causes accidents, the railway infrastructure is often not sufficiently adapted to traffic conditions and pedestrians' needs. Many preventive measures can be implemented to improve traffic safety and prevent traffic accidents and incidents, starting from improvements in legislation [24], infrastructure, signaling [25-27], and, especially, risky human behavior [28].

In this research, the trespassing problem at pedestrian-rail traffic flow intersection zones was analyzed. Daily migrations of citizens require them to cross the main (busy) railway line. Illegal pedestrian crossings across the railway line in the Zagreb settlement of Vrapče are the result of the poor condition and construction of pedestrian infrastructure. By illegally crossing the railway line every day, pedestrians endanger themselves and other rail transport users, thereby compromising the safety of the transport system. Two critical locations with "wild crossings" were observed (eastern and western). An analysis of the existing transport infrastructure showed that there are legal ways to cross the railway at both locations. Pedestrians who cross the railroad illegally do so for several obvious reasons—namely, shorter crossing times, shorter distances, and the absence of obstacles preventing them from crossing illegally.

Three new proposed solutions aim to prevent trespassing and encourage pedestrians to cross railway tracks legally. With each variant, improvement measures were proposed separately in the eastern and western locations of interest. The variants were evaluated using the AHP method, and the optimal variant was selected based on relevant criteria and their sub-criteria.

The selected optimal solution for meeting the criteria of safety and increasing urban mobility was determined. Building new underpasses at both locations and adding separate bicycle paths at the eastern site significantly enhanced pedestrian and cyclist safety and urban mobility. Beyond these primary objectives, the third variant also addresses secondary objectives critical to the local community in Vrapče, such as enhancing the area's attractiveness and improving residents' quality of life. It is essential to encourage walking and cycling over short distances; however, this cannot be achieved without adequate infrastructure. The optimal solution provides citizens with a simple, safe, and quick, environmentally friendly way to travel, specifically for walking and biking in the intersection zones of pedestrian and railway traffic.

This study demonstrates how targeted infrastructure changes can effectively reduce railway trespassing, but such changes come with several challenges. Constructing new underpasses involves high costs (construction and maintenance), long timelines, and coordination among several stakeholders. Moreover, community involvement is crucial, as local residents must be informed and engaged so they use the new crossings rather than circumvent them. Infrastructure alone may not change people's behavior immediately. However, by making legal crossings accessible and user-friendly, Variant 3 is expected to discourage people from taking shortcuts. Combining physical barriers with education and enforcement yields better outcomes [7]. After building the new underpasses, signage and awareness campaigns should remind pedestrians of the dangers of trespassing, and providing a safe, straightforward crossing path (as in Variant 3) could shift pedestrians' behavior by making illegal crossings inconvenient. Younger pedestrians, in particular, can be reached through school programs and interactive campaigns.

After implementing the optimal solution, its effectiveness must be measured. Monitoring and evaluation could be performed by establishing pre-implementation baselines and then periodically collecting the same data types used in this research. Video or sensor monitoring of the sites can count any remaining illegal crossings, legal underpass usage, and even train delays. Recording trespass incident reports and near-misses will indicate safety impacts. User surveys or community feedback can assess perceived safety and convenience.

## 7. CONCLUSIONS

Illegal pedestrian crossings over railway tracks pose a serious safety issue, especially when existing safe crossings are inconvenient. This study adds to international research by evaluating multiple

infrastructure variants and considering behavioral context in a Croatian city, complementing global findings on rail trespass prevention. The Vrapče case in the western part of Zagreb was analyzed, and three solution variants are proposed. Using a multi-criteria AHP approach, we found that the most comprehensive solution (Variant 3), which combines fences, anti-trespass panels, and multiple accessible underpasses, best met the goals of eliminating trespassing, enhancing safety, and improving mobility. These findings support urban transport policies that prioritize pedestrian safety infrastructure. By making legal routes safer and more attractive and by monitoring outcomes over time, cities can significantly reduce dangerous pedestrian behavior, including trespassing.

This study has several limitations. As a single-case study, the findings are most directly applicable to the specific context analyzed. Although comparable locations with similar challenges were identified elsewhere in Zagreb, further research is needed to assess the applicability of the results to other locations. Additionally, only preliminary cost estimates were developed, and the absence of a formal cost–benefit analysis limits our ability to evaluate the economic viability of the recommended option fully. This constraint reduces the immediate utility of the findings for decision-makers who must weigh technical performance against financial considerations.

Future research should address these limitations by applying the methodology to additional locations to test the current findings' generalizability, integrating detailed economic evaluations to support investment decisions, and monitoring post-implementation outcomes to assess long-term behavioral and safety impacts. Such efforts would strengthen the evidence base for designing effective, context-sensitive strategies to reduce hazardous pedestrian behavior and prevent railway trespassing.

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