Traffic & Transportation

Risk Analysis of Level Crossing Element Failures in a Fuzzy Environment

Milivoje ILIĆ[1], Đorđe MAKSIMOVIĆ[2], Norbert PAVLOVIĆ[3], Ivan BELOŠEVIĆ[4]

Original Scientific Paper
Submitted: 4 Dec 2023
Accepted: 2 Apr 2024

[1] m.ilic@sf.bg.ac.rs, University of Belgrade, Faculty of Transport and Traffic Engineering
[2] djordje.maksimovic@pupin.rs, Institute Mihailo Pupin
[3] norbert@sf.bg.ac.rs, University of Belgrade, Faculty of Transport and Traffic Engineering
[4] i.belosevic@sf.bg.ac.rs, University of Belgrade, Faculty of Transport and Traffic Engineering

This work is licenced under a Creative Commons Attribution 4.0 International Licence.

Publisher:
Faculty of Transport and Traffic Sciences,
University of Zagreb

ABSTRACT

The concept of risk analysis is especially important because it examines and analyses in a detailed manner the factors that affect the normal functioning of a system. In this paper, the level crossing is considered as one system, composed of several elements. The failures of those elements were analysed with the aim of showing which are the most frequent and most critical failures. A multi-methodological approach was used in the analysis. The failure modes and effects analysis (FMEA) method was used to determine risk factors, after that a multi-criteria model was created in a fuzzy environment, and as output, it gave a ranking list of critical failures in the system. Through the discussion of the results, a comparison of the basic model with two other similar ones was made, and the comparative results were analysed. The main aim of this paper is to present one of the possible ways to analyse the risk of the system of level crossings with the aim of improving traffic safety at the crossing.

KEYWORDS

level crossing; risk analysis; failure modes and effects analysis (FMEA); fuzzy approach; TOPSIS.

1. INTRODUCTION

Level crossings are places where road traffic lanes, i.e. the roadway, intersect with the railway, i.e. the upper edge of the rails at the same level. These places are places of high-risk zones for traffic safety due to the possibility of contact between the train and the road vehicle. The most frequent accidents at level crossings have very serious consequences and often result in deaths, primarily of road traffic participants. The reason for this is the very large differences in the speed of movement of road and railway vehicles, their structural characteristics and mass, and the length of the stopping distance. Accidents that occur at live crossings are mostly attributed to the railway as the responsible party in the mass media. Statistical analysis indicates that the main cause of accidents is the behaviour of road traffic participants (drivers of motor vehicles, cyclists and pedestrians) who knowingly or unknowingly did not comply with traffic regulations [1]. On average, the number of people killed at level crossings represents one-third of all people killed in railway traffic, and only 1–2% of people killed in road traffic. For this reason, level crossings do not represent a major safety problem in the road sector [2].

Considering that level crossings represent high-risk places; it is necessary that they are adequately insured. Regarding the safety system, level crossings can be secured with passive or active signalling. Passive signalling systems are equipped with road signalling traffic signs. These include the mandatory stop sign “Stop” and the “St. Andrew’s Cross” traffic sign with a secured zone of visibility from the road to the railway. Active signalling safety systems represent insurance in which there is a change in the state of the system (light-sound and/or mechanical) in relation to the arrival of a railway vehicle. This change of state can be controlled manually by an authorised worker at the crossing itself or remotely from an official place. Active safety systems, in addition to road signs, contain light and sound signalling with or without half-barriers and barriers.

Passive and active signalling systems belong to the group of level crossings that cross at the same level. However, there is also another group according to the way the road and railway cross, and that is out of level. Crossing a road and a railway outside the level implies the construction of an underpass or an overpass so that physical contact with the vehicles of these two types of traffic is impossible. The advantage of building such road crossings is that they offer the highest level of safety. However, they have one major drawback, which is that such a crossing takes up a large area around the intersection of the road and the railroad (unlevel road access to the intersection of the road and the railroad), which implies large investments. For this reason, the construction of such road crossings must be justified [3].

In this paper, the level crossing is observed as a system, secured by active signalling, and some of the possible failures of individual elements or sub-elements of the system are shown. A multiple approach to analysis was used, combining the failure modes and effects analysis (FMEA) method in a fuzzy environment and a multi-criteria model created using the TOPSIS method (techniques for order preference by similarity to ideal solution). These methodological approaches will be discussed in more detail in the next chapter.

There are numerous papers from various scientific fields that contain some form of the FMEA method. A group of authors headed by Oyang et al. considered a model of multiple perspectives of risk analysis factors in the FMEA method [4]. They proposed a new classification method by combining risk factors in pairs (S&O (severity and occurrence), S&D (severity and detection), O&D (occurrence and detection)). The authors combined FMEA and the functional resonance analysis method (FRAM) on the example of a nuclear-powered icebreaker [5]. In the paper [6] the Delphi-FMEA model was applied to prioritise risks in traffic accidents.

In the paper [7], the authors developed a model that includes statistical risk assessment using Bayesian networks. Using this approach, they analysed various influencing factors that can cause accidents at level crossings.

The paper [8] deals with the creation of a methodology for the identification of risks regarding the safety of railway traffic at level crossings. In the process of creating this methodology, a modified FMEA method was used.

Žitnikova et al. performed an analysis of traffic safety at level crossings in one region from the technical and legislative aspects, as well as the participation of human errors in the occurrence of accidents at level crossings. Using the FMEA method, they determined risk scenarios and made suggestions for improving traffic safety at crossings [9].

The application of the fuzzy-TOPSIS method is shown in the paper of the author Kasalica et al., on the example of a level crossing. The authors considered additional safety measures at the level crossing according to certain criteria in order to increase traffic safety at the crossing [10].

Level crossings represent a very good basis and proctor, which is very suitable for conducting various research regarding the application of different methodologies and approaches, all with the aim of increasing traffic safety at level crossings [11–14].

2. METHODOLOGY

In this chapter, the basic concepts of the methods used in this work will be discussed. These are the FMEA method, the fuzzy approach and fuzzy sets, as well as the TOPSIS multi-criteria decision-making (MCDM) method.

2.1 FMEA method

FMEA (failure modes and effects analysis) belongs to a group of engineering methods and techniques for quality improvement. FMEA is a method used to evaluate the modes and effects of potential failures of subsystems, assemblies, components or functions in a system. FMEA is an inductive, team method that requires time and a good knowledge of the system being analysed. The goal of the method is to identify failures that can adversely affect the reliability of the entire system. FMEA is most often used in the initial stages of development to ensure that all potential failures are detected and eliminated in time. FMEA applies to any system and any desired level of detail – system, subsystem, assembly or component. In the short term, FMEA lists potential failures and identifies the severity of their effects and prioritises correction. In the long term, FMEA develops criteria for planning system testing; provides documentation for future reliability analysis in case of system design changes; provides a basis for maintenance planning; provides a basis for qualitative and quantitative analysis of system reliability.

FMEA is a very important technique used to identify and eliminate known and potential system/subsystem failures. The aim of this method is to increase the reliability and security of the system and is very important in terms of risk analysis. The basic terms used in FMEA are:

1) Failure – deviation from the planned function or behaviour; the inability of a system, subsystem or component to perform a required function.
2) Failure mode – the way in which the element fails; the shape or state of the element in which the element is after failure.
3) Failure cause – the process or mechanism responsible for initiating the failure. Processes that can cause component failure are e.g. physical failure, model defect, manufacturing defect, environmental impact, etc.
4) Failure effect – consequence of a failure on the functioning or status of an element and system.

The basic concept of the FMEA method implies the decomposition of the system into its component elements, up to a level depth that has been assessed as significant for the analysis.

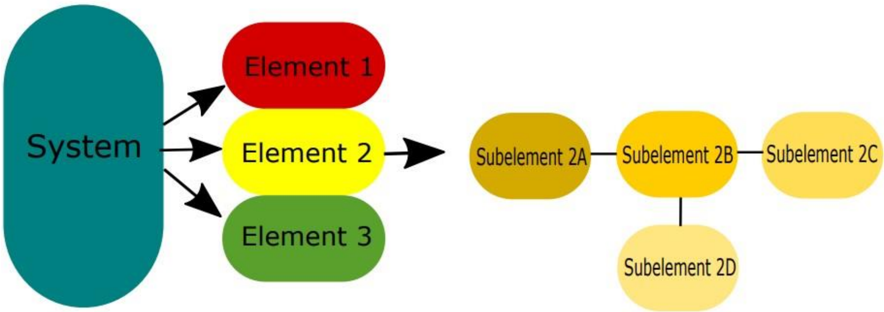

Figure 1 – FMEA concept

Depending on the application, FMEA is classified as production FMEA or process FMEA. A manufacturing FMEA analyses a product or system design by examining how element failure affects the product or system. A process FMEA analyses the processes involved in the production, use and maintenance of a product. Examines how process failures affect a product or system. By way of implementation, FMEA can be functional and structural. In the functional one, the system is analysed from the aspect of its functionality and decomposed into sub-functions. In structural FMEA, the system is analysed from the aspect of its structure (components). According to Stamatis, there are 4 types of FMEA methods: system, design, process and service FMEA [15]. The classification is based on the practical application of the method itself. The first step is to identify possible system failures, after which a critical failure analysis is performed, taking into account risk factors: occurrence (O), severity (S) and detection (D). The risk priorities of failure modes are determined through the risk priority number (RPN), which is the product of the O, S and D of a failure. That is

$$RPN = O \cdot S \cdot D \tag{1}$$

where occurrence (O) is the probability of the failure, severity (S) is the severity of the failure and detection (D) is the probability of not detecting the failure. These three risk factors could be valued and graded on the basis of scales. Scales can be universal (e.g. from 1 to 10) or can be formulated for the specific system being analysed. Based on the RPN, the ranking is obtained and the elements can be sorted according to the highest or lowest number, that is, the highest or lowest risk of failure (such as those shown in *Tables 1-3*).

Table 1 – FMEA scale for severity (S)

Severity of effect	**Rating**
There is no reason to expect that the failure will have an effect on safety, health, the environment or the mission.	1
Slight functional impairment. The repair can be completed as soon as the failure is noticed.	2
Slight functional impairment. The repair may take longer but will not compromise the mission.	3
Moderate functional impairment. Some parts of the mission must be reworked or parts of the process delayed.	4
Moderate functional impairment. The entire mission must be reworked or the entire process postponed.	5
Moderate functional impairment. Some parts of the mission are lost. Moderate delay in system recovery.	6
Major dysfunction. Some parts of the mission are lost. Significant delay in system recovery.	7
Major dysfunction. The whole mission is lost. Significant delay in restoring the system. Cancellation occurs without warning.	8
Potential danger to safety, health or the environment. Cancellation occurs with a warning.	9
Potential danger to safety, health or the environment	10

Table 2 – FMEA scale for occurrence (O)

Effects and occurrence	**Rating**
Remote. The failure is almost unbelievable.	1
Very low. Very rare failures.	2
Low. Relatively few failures.	3
Low to moderate. Infrequent failures.	4
Moderate. Occasional failures.	5
Moderate to high. Frequent failures.	6
High. Failures occur frequently.	7
High. Failures are repeated.	8
Very high. Failures and failure free operations are almost the same.	9
Extreme. Failure is almost inevitable.	10

Table 3 – FMEA scale for detection (D)

Detection	**Rating**
Almost certain	1
Very high	2
High	3
Moderately high	4
Moderate	5
Low	6
Very low	7
Remote	8
Very remote	9
Absolute uncertainty	10

2.2 Fuzzy set theory and linguistic variables

Fuzzy set theory was developed by Zadeh as a conceptual framework to treat uncertain and imprecise situations existing in real life [16]. Incorporating fuzzy set theory in the MCDM methodology, Bellman and Zadeh introduced a mathematically precise way of treating vagueness and subjectivity in assigning criteria weights and performance rating of each alternative regarding evaluation criteria [17]. So far, various MCDM methods have been extended under fuzzy environment and applied in different fields of engineering or management [18–20]. In this paper, we involve the application of fuzzy logic and TOPSIS method with the aim of ranking the critical elements of the level crossing system.

For the sake of simplicity, we utilise triangular fuzzy numbers to represent linguistic variables in this paper. In the literature [21, 22], a triangular fuzzy number $\tilde{A} = (a_1, a_2, a_3)$ is determined as a triplet of crisp numbers such that $a_1<a_2<a_3$ (see *Figure 2*). The function value $\mu_{\tilde{A}}(x)$ stands for the membership degree of x in $\tilde{A}$, such that a higher $\mu_{\tilde{A}}(x)$ means a higher degree of belongingness for x in $\tilde{A}$ (see *Equation 2*).

$$\mu\tilde{A}(x) = \begin{cases} 0, & x < a1 \\ \frac{x-a1}{a2-a1}, & a1 < x < a2 \\ \frac{a3-x}{a3-a2}, & a2 < x < a3 \\ 0, & x > a3 \end{cases} \tag{2}$$

According to [23], the distance between two triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{N} = (n_1, n_2, n_3)$ can be derived utilising the vertex method (see *Equation 3*). Although the crisp value of the triangular fuzzy number can be derived utilising different defuzzification methods, we apply the centroid method in this paper (see *Equation 4*).

$$d(\tilde{A}, \tilde{N}) = \sqrt{\frac{[(a1-n1)^2 + (a2-n2)^2 + (a3-n3)^2]}{3}} \tag{3}$$

$$x0(\tilde{A}) = \frac{a1+a2+a3}{3} \tag{4}$$

Within a decision-making process, experts often tend to use linguistic variables to accommodate the fuzziness contained in their judgments. The following sets of linguistic terms with their corresponding triangular fuzzy numbers (see *Figure 3*) are adopted to express values of linguistic variables in order to evaluate criteria weights and ratings of alternatives.

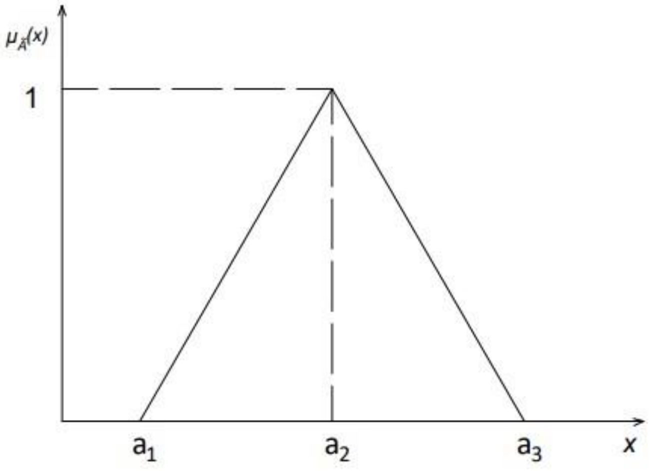

Figure 2 – Triangular fuzzy number

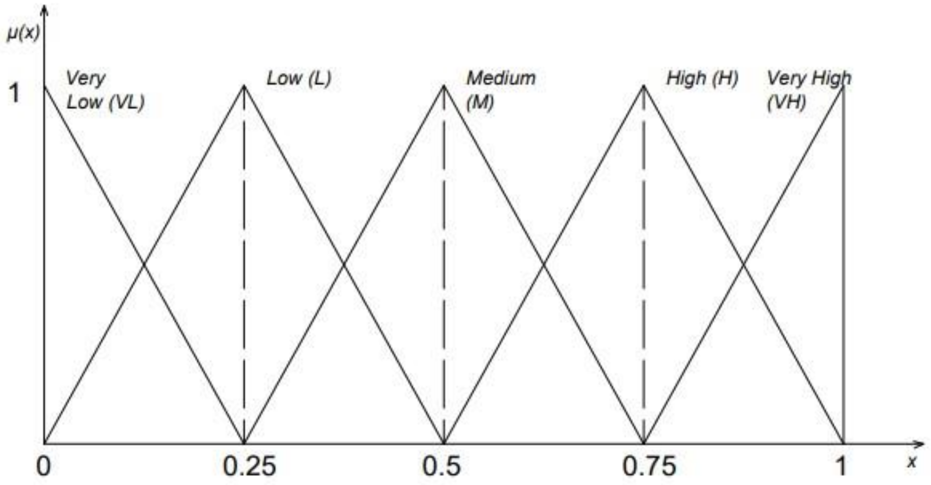

Figure 3 – Linguistic variable

2.3 TOPSIS method

The TOPSIS (techniques for order preference by similarity to ideal solution) method defines a solution from the final group of elements based on the distance measure from the ideal solution. The application of this principle of measuring the distance from the ideal solution in TOPSIS eliminates the possibility of subjective decision-making [24]. The ranking of alternatives is based on a measure of relative closeness to the ideal solution and a measure of relative distance from the anti-ideal solution. An ideal solution represents a combination of the best alternative values for each criterion, and an anti-ideal solution represents a combination of the worst alternative values for each criterion. Ideal and anti-ideal solutions are defined for each criterion separately, taking into account whether the criterion is of minimisation or maximisation type. The algorithm of the TOPSIS method consists of the following steps (see *Figure 4*):

1) Formation of the starting decision matrix for alternatives (A_1, A_2 , ..., A_m) according to the adopted criteria (C_1,C_2,...C_n) and criteria functions (f_1, f_2,...f_n). The matrix element represents the values of *j* criteria function for *i* alternative.
2) Normalisation of values of the starting decision matrix is performed with the aim of reducing values to a dimensionless value according to the relation below (see *Equation 5*).

$$x_{ij} = \frac{f_{ij}}{\sqrt{\sum_{i=1}^{n} f_{ij}^2}} \tag{5}$$

3) Determination of weighted criteria values (w_1, w_2,...w_n) and formation of weighted normalised matrix. Matrix element v_{ij} represents the multiplication of weighted criteria value v_{ij} and normalised alternative value x_{ij}.
4) Determination of ideal solution (A^*) and anti-ideal solution (A^-) as a combination of best (v_j^*) and worst (v_j) alternative values by all criteria (see *Equation 6*).

$$A^* = \{v_1^*, v_2^*, \ldots, v_m^*\}, \qquad A^- = \{v_1^-, v_2^-, \ldots, v_m^-\} \tag{6}$$

5) Determination of relative separation measures of alternatives from the ideal solutions (see *Equation 7*).

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^*\right)^2}, \quad S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad i = 1, \ldots, m \tag{7}$$

6) Determination of the relative closeness to the ideal solution (see *Equation 8*).

$$\,_i^{*} = \frac{S_i^-}{S_i^* + S_i^-}\ ,\ i = 1, \dots, m \tag{8}$$

7) Ranking alternatives according to relative closeness to the ideal solution.

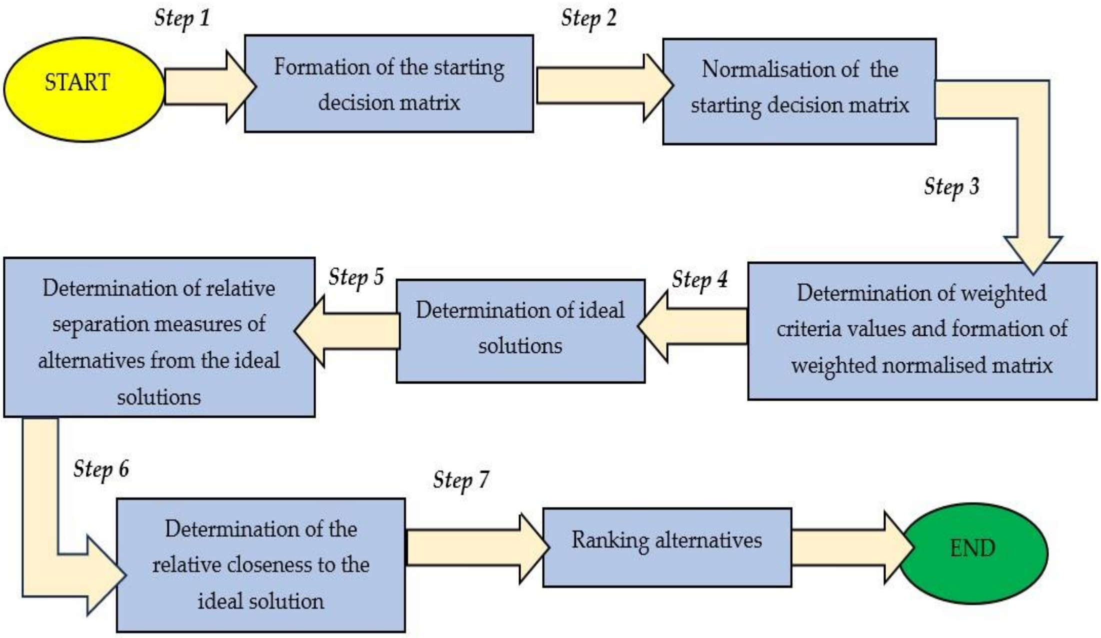

Figure 4 – TOPSIS algorithm

3. AN ILLUSTRATIVE EXAMPLE

As already mentioned, level crossings are places where the railway and the road cross on the same level. Given that this intersection is an area of very high risk for the safety of road users, it is necessary to take all measures to reduce the number of accidents at crossings and mitigate their consequences. One of the factors that can negatively affect the normal flow of traffic on the crossings is the functionality of the level crossing security device.

In this example, we looked at certain structural elements that make up the level-crossing system. Some of the most common failures and malfunctions of individual sub-elements of this system are processed in the framework of these elements. A detailed analysis was carried out with the help of experts and 27 types of failure were selected as part of a group of 7 constituent elements of the level crossing. The experts are engineers from 3 different professions related to level crossings (LC) and they gave their linguistic ratings for each failure according to the appropriate criteria (severity, occurrence and detection) used in the model (see *Table 4*). There were 3 experts from each profession, and the ratings shown for each group of experts represent their combined ratings. *Table 5* shows linguistic evaluations by experts for the importance of each criterion.

Linguistic ratings shown in *Tables 4 and 5* were transformed into triangular fuzzy numbers. The fuzzy numbers are aggregated so that one common fuzzy value is obtained taking into account all 3 expert opinions, as shown in *Table 6*. After that, the values from the aggregated matrix are defuzzified using *Equation 4*, (see *Table 7*). In *Table 7*, a defuzzified matrix is shown, where one of the three values from *Table 6* is shown, which represents them.

Table 4 – Rating of alternatives with respect to criteria

			DM1			**DM2**			**DM3**		
	Element	**Failure**	**S**	**O**	**D**	**S**	**O**	**D**	**S**	**O**	**D**
1	LC control system	Failure of the microswitch to control the final position of the barriers in one setting device.	L	M	VL	M	M	VL	M	M	VL
2		Failure of the microswitch to control the final position of the barriers in both setting devices.	L	L	VL	M	L	VL	M	L	VL
3		Failure of engine.	M	L	VL	H	M	VL	M	L	L
4		Failure of the electromagnetic brake.	M	L	VL	M	M	VL	M	L	L
5		Mechanical lever failure (for devices where the closing of the passage is done by gravity).	M	L	VL	M	M	L	M	L	L
6		Mechanical lever failure after power loss.	M	L	VH	M	L	VH	H	L	H
7		Fracture of half-barrier or barrier.	L	M	VL	M	M	VL	L	M	VL
8		Interruption of the cable for checking the integrity of the half-barrier or barrier.	L	L	VL	M	L	VL	M	L	VL
9		Interruption of the cable for controlling the final position of the half-barrier or barrier.	L	L	VL	M	L	VL	M	L	VL
10		Forcible retention of the half-barrier or barrier during lowering or raising.	L	L	VL	L	M	VL	H	L	VL
11	LC activation point	Failure of one of the two activation devices.	L	M	VL	M	M	VL	M	M	VL
12		Failure of both electronic activation devices.	L	L	L	M	L	M	H	VL	VL
13		Failure of both activation devices – punctual type (broken mechanical pedal or stuck magnetic-rail contact).	VH	L	VH	VH	VL	VH	VH	L	VH
14		Magnetic-rail contact on the activation device – due to iron filings false activation.	L	L	VL	M	M	VL	M	M	VL
15		Interruption of the cable for the control of the activation device.	L	L	VL	M	L	VL	M	L	VL
16	LC deactivation point	Failure of one of the two deactivation devices, during a switch-off level crossing (raised half-barrier or barrier).	L	L	VL	M	M	VL	M	L	L
17		Failure of both deactivation devices, during a switch-off level crossing (raised half-barrier or barrier).	L	M	VL	M	L	VL	M	L	L
18		Failure of one of the two deactivation devices, during a switch on level crossing (lower half-barrier or barrier).	L	L	VL	H	M	VL	M	L	L
19		Failure of both deactivation devices, during a switch on level crossing (lower half-barrier or barrier).	M	L	VL	M	M	VL	H	L	H
20		Interruption of the cable for controlling the deactivation device.	M	L	VL	M	M	L	L	M	VL
21	Railway block signal device	Failure of the block section or shield block signal.	M	L	VL	M	L	VH	M	L	VL
22		Failure of permission, driving under “contra-permission”.	M	L	VH	M	M	VL	M	L	VL
23	Interlocking system	Extended train travel time from the activation point to the level crossing zone.	L	M	VL	M	L	VL	H	L	VL
24	Power supply of LC	Interruption of power supply.	L	L	VL	M	L	VL	M	M	VL
25		Battery failure.	L	L	VL	L	M	VL	H	VL	VL
26	Road signal	One fibre on the light bulb on the road signal has burned out.	L	L	VL	M	M	VL	VH	L	VH
27		Both fibres on the light bulb on the road signal have burned out.	L	M	VL	M	L	M	M	L	VL

Table 5 – Importance weight of criteria assessed by decision-makers

	C_1 (S)	**C_2 (O)**	**C_3 (D)**
DM_1	VH	M	M
DM_2	VH	M	H
DM_3	H	L	M

Table 6 – Aggregated fuzzy ratings and subjective fuzzy weights

Criteria	**S**	**O**	**D**
Weights	(0.5; 0.92; 1)	(0; 0.42; 0.75)	(0.25; 0.58; 1)
1	(0; 0.42; 0.75)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
2	(0; 0.42; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
3	(0.25; 0.58; 1)	(0; 0.33; 0.75)	(0; 0.08; 0.5)
4	(0.25; 0.5; 0.75)	(0; 0.33; 0.75)	(0; 0.08; 0.5)
5	(0.25; 0.5; 0.75)	(0; 0.33; 0.75)	(0; 0.17; 0.5)
6	(0.25; 0.58; 1)	(0; 0.25; 0.5)	(0.5; 0.92; 1)
7	(0; 0.33; 0.75)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
8	(0; 0.42; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
9	(0; 0.42; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
10	(0; 0.42; 1)	(0; 0.33; 0.75)	(0; 0; 0.25)
11	(0; 0.42; 0.75)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
12	(0; 0.5; 1)	(0; 0.17; 0.5)	(0; 0.25; 0.75)
13	(0.75; 1; 1)	(0; 0.17; 0.5)	(0.75; 1; 1)
14	(0; 0.42; 0.75)	(0; 0.33; 0.75)	(0; 0; 0.25)
15	(0; 0.5; 1)	(0; 0.25; 0.5)	(0; 0; 0.25)
16	(0; 0.42; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
17	(0; 0.42; 0.75)	(0; 0.08; 0.5)	(0; 0; 0.25)
18	(0; 0.42; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
19	(0.25; 0.5; 0.75)	(0; 0.17; 0.5)	(0; 0.5; 1)
20	(0.25; 0.5; 0.75)	(0; 0.25; 0.5)	(0; 0; 0.25)
21	(0; 0.42; 1)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
22	(0; 0.42; 1)	(0; 0.33; 0.75)	(0; 0; 0.25)
23	(0.25; 0.58; 1)	(0; 0.33; 0.75)	(0.75; 1; 1)
24	(0; 0.33; 0.75)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
25	(0; 0.42; 1)	(0; 0.33; 0.75)	(0; 0; 0.25)
26	(0; 0.33; 0.75)	(0.25; 0.5; 0.75)	(0; 0; 0.25)
27	(0; 0.42; 0.75)	(0; 0.17; 0.5)	(0; 0; 0.25)

Table 7 – Defuzzified values

Criteria	S	O	D
Weights	0.81	0.39	0.61
1	0.39	0.50	0.08
2	0.39	0.25	0.08
3	0.61	0.36	0.19
4	0.50	0.36	0.19
5	0.50	0.36	0.22
6	0.61	0.25	0.81
7	0.36	0.50	0.08
8	0.39	0.25	0.08
9	0.39	0.25	0.08
10	0.47	0.36	0.08
11	0.39	0.50	0.08
12	0.50	0.22	0.33
13	0.92	0.22	0.92
14	0.39	0.36	0.08
15	0.50	0.25	0.08
16	0.39	0.25	0.08
17	0.39	0.19	0.08
18	0.39	0.25	0.08
19	0.50	0.22	0.50
20	0.50	0.25	0.08
21	0.47	0.50	0.08
22	0.47	0.36	0.08
23	0.61	0.36	0.92
24	0.36	0.50	0.08
25	0.47	0.36	0.08
26	0.36	0.50	0.08
27	0.39	0.22	0.08

In this analysis, for the defining of weighted coefficients the eigenvector method is used. In the first step, the comparison of the criteria relevance is performed using the k_{ij} values, resulting in the Saaty scale [25]. The matrix for criteria comparison is presented in *Table 8*. Normalised values of the weighted coefficients are the results of the relation (see *Equation 9*). The values of these weighted coefficients are presented in *Table 9* and have a consistency ratio of 0.008, totally acceptable under the principle described in [26].

$$w_j = \frac{\sum_{j=1}^{n} \frac{k_{ij}}{\sum_{i=1}^{n} k_{ij}}}{n} \tag{9}$$

Table 8– Comparison of criteria using the Saaty scale

	C_1	C_2	C_3
C_1	1	3	2
C_2	1/3	1	1/2
C_3	1/2	2	1

Table 9 – The value of weights

	w_j
C_1	0.54
C_2	0.16
C_3	0.30

After forming the weighted normalised matrix according to the TOPSIS method algorithm, the ideal solution and anti-ideal solution are defined according to relation (see *Equation 6*). The values of the ideal solutions are shown in *Table 10*. The measure of the distance between the ideal solution and the anti-ideal solution is derived from the result based on a relation (see *Equation 7*) and is shown in *Table 11*. Based on the measure of the relative closeness of the alternatives to the ideal solutions, the comparison of the alternatives (rank list) follows from the relation (see *Equation 8*).

Table 10 – Values for ideal and anti-ideal solution

	C_1	**C_2**	**C_3**
A^*	0.08	0.02	0.01
A^-	0.20	0.05	0.16

Table 11 – Relative closeness to the ideal solutions and final ranking

	S_i^*	**S_i^-**	**C_i^***	**Rank**		**S_i^***	**S_i^-**	**C_i^***	**Rank**
1	0.0283	0.1837	0.8666	15	14	0.0162	0.1841	0.9190	20
2	0.0078	0.1851	0.9595	21	15	0.0303	0.1714	0.8496	10
3	0.0592	0.1419	0.7057	5	16	0.0078	0.1851	0.9595	21
4	0.0386	0.1545	0.7999	8	17	0.0060	0.1858	0.9688	27
5	0.0412	0.1506	0.7850	7	18	0.0078	0.1851	0.9595	21
6	0.1363	0.0722	0.3464	3	19	0.0781	0.1179	0.6014	4
7	0.0276	0.1875	0.8715	17	20	0.0303	0.1714	0.8496	10
8	0.0078	0.1851	0.9595	21	21	0.0366	0.1732	0.8257	9
9	0.0078	0.1851	0.9595	21	22	0.0283	0.1736	0.8599	12
10	0.0283	0.1736	0.8599	12	23	0.1548	0.0670	0.3022	2
11	0.0283	0.1837	0.8666	15	24	0.0276	0.1875	0.8715	17
12	0.0527	0.1375	0.7229	6	25	0.0283	0.1736	0.8599	12
13	0.1875	0.0251	0.1182	1	26	0.0276	0.1875	0.8715	17
					27	0.0065	0.1854	0.9662	26

4. DISCUSSION

In this chapter, in addition to the discussion of the results, a sensitivity analysis will also be presented. The sensitivity analysis in this work was reflected in the fact that comparisons of the ranks of different failures (alternatives) were made taking into account three models. The first model was presented in the paper and included a combination of the fuzzy-TOPSIS method with the objective weighting coefficients of the criteria determined using the AHP method. The second model also represented a combination of the fuzzy-TOPSIS method, but in this model, all criteria had the same importance and equal weight coefficients (w=0.33). The third model represented failure risk analysis using the classical FMEA method. Using relation (see *Equation 1*), the RPN was obtained as the product of the mean values of the numerical ratings obtained by the experts (from a scale of 1 to 10) for each criterion. In the following *Table 12* and *Figure 5*, a comparative view of the results and ranking of failures for all three models is shown.

Table 12 – Failures rank according to each model

	First model	**Second model**	**Third model**
1	15	8	10
2	21	21	25
3	5	6	6
4	8	14	7
5	7	13	5
6	3	3	3
7	17	10	20
8	21	21	17
9	21	21	17
10	12	15	22
11	15	8	16
12	6	5	8
13	1	2	2
14	20	18	13
15	10	19	12
16	21	21	14
17	27	27	26
18	21	21	14
19	4	4	4
20	10	19	17
21	9	7	9
22	12	15	11
23	2	1	1
24	17	10	20
25	12	15	22
26	17	10	22
27	26	26	27

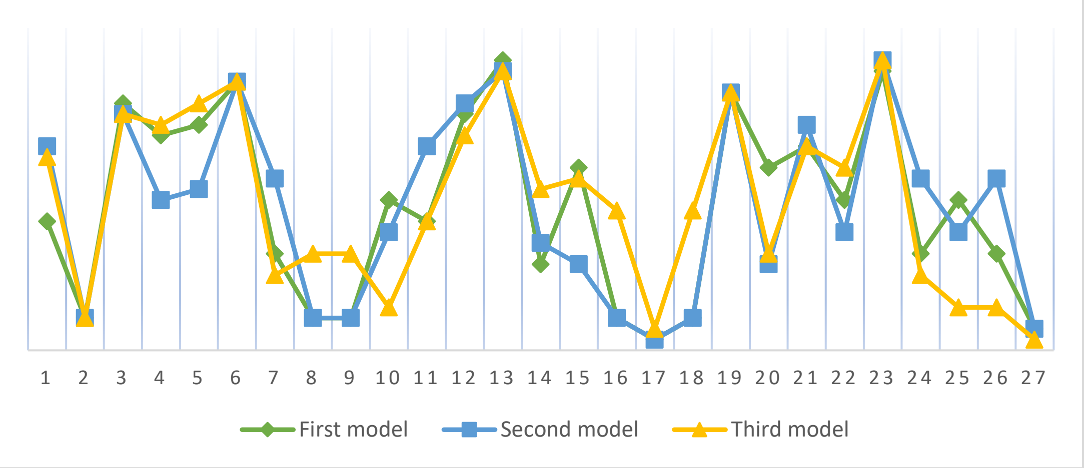

Figure 5 – Failures rank according to each model

Based on the table and the graph, it is possible to clearly conclude which are the most critical failures and which should be reduced. Based on the first model, it is clearly observed that the most critical failure is under number 13. Also in the high-risk zone are failures under numbers 23, 6 and 19. Other failures fall into a more moderate risk zone, while failure under number 17 is the least risky.

The second model shows that the most critical failure is the one under the number 23, while in the high-risk zone failures are 13, 6 and 19. Based on this model, it was obtained that compared to the previous one, failures 13 and 23 changed their places. This certainly does not change the fact that special attention should be paid to both dismissals. Other cancellations fall into a more moderate risk zone, while the least risky cancellation is number 17, as in the first model.

The third model, which is significantly different from the first two in its setup, showed that the most critical failure is number 23. As with the previous model, failures 13, 6 and 19 are in the high-risk zone. The least risky failure is number 27, which differs from previous models. Other cancellations fall under the medium risk category.

Common to all models is that generally, the most critical and least critical failures are in line. Each model produced results such that there is a large overlap in the ranking of the most critical and least critical failures. In the first two models, the same failure is the least critical (17), while in the second and third models, the same failure is the most critical (23). The first and second models for failures in the middle-risk zone give fairly similar results and their lines on the graph largely have the same direction and overlap in several places. This similarity stems from the same work methodology, and the differences represent only the weighting coefficients for the criteria. However, the third model has certain deviations for cancellations in the medium-risk zone. Namely, these differences are reflected in the way the FMEA method works. With this model, extreme values are visible, and they primarily come to the fore, leaving no significant impact on other values. Simply put, this model sets a slightly sharper line between the best/worst solutions and the rest.

5. CONCLUSION

Risk management, as well as risk analysis today represent one of the key aspects when modelling and later exploitation of many systems and assemblies. One of such assemblies is the level crossing. Considering the importance, function and potentially dangerous situations that can occur around the level crossing, it is necessary to pay maximum attention to all elements and all failures that can occur at the crossing, to eliminate and reduce their consequences.

This paper presents some of the most common failures and failures of individual elements within the level-crossing system in the Republic of Serbia in the period of the previous 5 years. Twenty-seven types of failures within 7 different elements of the system were analysed. Different methodologies were used as part of the analysis, which gave their results. At the very beginning, the risk factors used in the FMEA method were defined, and they were observed below as criteria in the multi-criteria analysis. Three groups of experts gave their ratings for each risk factor, which were later used in the analysis. Three models were developed, two of which were very similar and were based on the fuzzy-TOPSIS approach, while the third model represented the classic application of the FMEA method. All these models gave their output results based on which the ranking list of critical failures was created.

This approach and the combination of different methodologies contributed to the output results being better quality, more objective and clearer. The combined approach represents a very powerful tool for some future research in this domain. As part of further research, some other possible cancellations should be considered, as well as a larger number of elements for consideration. If extensive failure databases exist, the modelled results can be compared to them. It is also possible to use some other methods of multi-criteria analysis, as well as some other approaches to objectively determine the weight coefficients of the criteria, with the addition of another criterion if necessary.

REFERENCES

[1] Tordai L, Olpinski W, Schafer W, Wegele S. D1 - report about statistics, database analysis and regulations for level crossing, *SELCAT (Safer European Level Crossing Appraisal and Technology)*. Paris, France, 2008.

[2] Starčević M, Barić D, Pilko H. Survey-based impact of influencing parameters on level crossings safety. *Promet - Traffic&Transportation*. 2016;28(6):639–649. DOI:10.7307/ptt.v28i6.2208.

[3] Pavlović N, Starčević M, Belošević I, Nikšić M. Safety at level crossing comparative analysis between Serbia and Croatia. (In Serbian) *Železnice*. 2022,67(2):57-67. https://www.casopis-zeleznice.rs/index.php/zeleznice/article/view/106/98 [Accessed 14th May 2024].

[4] Ouyang L, Che Y, Yan L, Park C. Multiple perspectives on analyzing risk factors in FMEA. *Computers in Industry*. 2022;141:1–13. DOI:10.1016/j.compind.2022.103712.

[5] Fu S, et al. Towards a probabilistic approach for risk analysis of nuclear-powered icebreakers using FMEA and FRAM. *Ocean Engineering*. 2022;260. DOI:10.1016/j.oceaneng.2022.112041.

[6] Ebrahimi S, Vachal K, Szmerekovsky J. A Delphi-FMEA model to assess county-level speeding crash risk in North Dakota. *Transportation Research Interdisciplinary Perspectives*. 2022;16(1):1-11. DOI:10.1016/j.trip.2022.100688.

[7] Liang C, Ghazel M, Cazier O, El-Koursi E. Risk analysis on level crossings using a causal Bayesian network based approach. *WCTR 2016*. Shanghai, China, 10–15 July 2016. DOI:10.1016/j.trpro.2017.05.418.

[8] Nedeliakova E, Hranicky M, Valla M. Risk identification methodology regarding the safety and quality of railway services. *Production Engineering Archives*. 2022;28(1):21–29. DOI:10.30657/pea.2022.28.03.

[9] Žitnikova I, Schwarz M, Bernatik A. Assessment of the risk of level crossings in the Moravian-Silesian region and proposed safety measures. *Transactions of the VŠB - Technical University of Ostrava-Safety Engineering Series*. 2011;6(1):48–54. https://core.ac.uk/download/pdf/8992474.pdf [Accessed 14th May 2024].

[10] Milosavljević M, Kasalica S, Jeremić D, Vil G. Application of fuzzy TOPSIS method for selection the additional protecting system on railway crossing. *Proceedings of the XVIII International Scientific-Expert Conference on Railways- RAILCON 2018*. October 2018, Niš, Serbia. p. 57-60. 2018.

[11] Berrado A, El-Koursi E, Cherkaoui A, Khaddour M. A framework for risk management in railway sector: Application to road-rail level crossings. *Open Transportation Journal*. 2010;5(1):34–44. DOI:10.2174/1874447801105010034.

[12] Fayyaz MAB, Johnson C. Object detection at level crossing using deep learning. *Micromachines*. 2020;11(12):1055. DOI:10.3390/mi11121055.

[13] Pamučar D, Lukovac V, Božanić D, Komazec N. Multi-criteria FUCOM-MAIRCA model for the evaluation of level crossings: Case study in the Republic of Serbia. *Operational Research in Engineering Sciences: Theory and Applications*. 2018;1(1):108–129. DOI:10.31181/oresta190120101108p.

[14] Ballay M, Sventekova E, Kubiatko T, Macurova L. The impact of critical elements on the formation and consequences of accidents at railway crossings. *Proceedings of 23rd International Scientific Conference Transport Means*. Kaunas, Lithuania. 2019. https://www.tf.lbtu.lv/conference/proceedings2022/Papers/TF271.pdf [Accessed 14th May 2024].

[15] Stamatis DH. *Failure mode and effect analysis: FMEA from theory to execution*, 2nd edition, ASQ Quality Press, Milwaukee, Wisconsin, USA. 2003.

[16] Zadeh LA. Fuzzy sets. *Information and Control*. 1965;8(3):338–353. DOI:10.1016/S0019-9958(65)90241-X.

[17] Bellman RE, Zadeh LA. Decision-making in a fuzzy environment. *Management Science*. 1970;17(4):141–164. DOI: 10.1287/mnsc.17.4.B141.

[18] Mardani A, Jusoh A, Zavadskas EK. Fuzzy multiple criteria decision-making techniques and applications – Two decades review from 1994 to 2014. *Expert System with Applications*. 2015;42(8):4126–4148. DOI:10.1016/j.eswa.2015.01.003.

[19] Shafabakhsh G, Hadjihoseinlou M, Taghizadeh SA. Selecting the appropriate public transportation system to access the Sari International airport by fuzzy decision making. *European Transport Research Review*. 2014;6(3):277–285. DOI:10.1007/s12544-013-0128-7.

[20] Gajzler M, Zima K. Evaluation of planned construction projects using fuzzy logic. *International Journal of Civil Engineering*. 2017;15(4):641–652. DOI:10.1007/s40999-017-0177-8.

[21] Cheng CH, Lin Y. Evaluating the best main battle tank using fuzzy decision theory with linguistic criteria evaluation. *European Journal of Operational Research*. 2002;142(1):174–186. DOI:10.1016/S0377-2217(01)00280-6.

[22] Chen LY, Wang TC. Optimizing partners' choice in IS/IT outsourcing projects: the strategic decision of fuzzy VIKOR. *International Journal of Production Economics*. 2009;120(1):233–242. DOI:10.1016/j.ijpe.2008.07.022.

[23] Chen CT. Extensions of the TOPSIS for group decision-making under fuzzy environment. *Fuzzy Sets and Systems*. 2000;114(1):1–9. DOI:10.1016/S0165-0114(97)00377-1.

[24] Olson DL. Comparison of Weights in TOPSIS Models. *Mathematical and Computer Modelling*. 2004;40(7):721–727. DOI:10.1016/j.mcm.2004.10.003.

[25] Saaty TL. How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*. 1990;48(1):9–26. DOI:10.1016/0377-2217(90)90057-I.

[26] Saaty TL. *Fundamentals of decision making and priority theory with AHP*, RWS Publications, Pittsburgh, Pennsylvania, USA. 1994.

Milivoje Ilić, Đorđe Maksimović, Norbert Pavlović, Ivan Belošević

Analiza rizika elemenata putnog prelaza u fazi okruženju

Sažetak

Koncept analize rizika je posebno važan jer se njime detaljno ispituju i analiziraju faktori koji utiču na normalno funkcionisanje sistema. U ovom radu pružni prelaz se razmatra kao jedan sistem, sastavljen od više elemenata. Analizirani su otkazi tih elemenata sa ciljem da se pokaže koji su najčešći i najkritičniji otkazi. U analizi je korišćen multimetodološki pristup. Za utvrđivanje faktora rizika korišćena je metoda Failure Modes and Effects Analisis (FMEA), nakon čega je kreiran višekriterijumski model u fazi okruženju, koji je kao izlaz dao rang listu kritičnih otkaza u sistemu. Kroz diskusiju rezultata izvršeno je poređenje osnovnog modela sa još dva slična i analizirani su uporedni rezultati. Osnovni cilj ovog rada je da predstavi jedan od mogućih načina analize rizika sistema pružnih prelaza u cilju unapređenja bezbednosti saobraćaja na prelazu.

Ključne reči

Putni prelaz, Analiza rizika, Failure Modes and Effects Analysis (FMEA), Fazi pristup, TOPSIS.