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INFLUENCE OF TRACK GEOMETRY CONDITION MONITORING ON RAILWAY INFRASTRUCTURE MAINTENANCE PROCESSING

Summary. This study analyzed the usage of data of track geometry measurement for railway infrastructure maintenance processing support and estimated its influence on railway infrastructure maintenance decision-making. Especially, the approach assessment of the influence of track geometry monitoring on railway infrastructure processing. The well-timed maintenance of the arrangement of railway tracks in allowable conditions is sufficient for the smooth and steady running of rail vehicles. The mechanism of track gauge widening during exploitation is usually gradual and relatively long-lasting. When are not detected in a timely manner, the final track failures often arise under the effect of additional factors, such as surpassed train speed limit, poorly maintained and functioning running gear of a rail vehicle, misalignment of rails, and extreme dynamical effects. A questionnaire considering the influence of the application of track geometry monitoring was formulated. An expert review was completed in order to perform a comparative analysis of the features of track geometry monitoring with the greatest influence on railway infrastructure maintenance processing. The data collected from respondents were processed using a multi-criterion estimation method, especially an interactive fuzzy linear assignment method. Finally, basic conclusions and considerations are given.

1. INTRODUCTION

Railway track degradation has attracted much attention. Intensive research activities have been conducted by many organizations targeting not only to secure a high level of safety and reliability of railway infrastructure (RI) systems but also to diminish the problems associated with the degradation of performance in terms of train ride quality and stability, passenger comfort, traffic safety, energy efficiency, among other issues. Track maintenance typically includes repairing rails and tending to track geometry (i.e., fastening components, the ballast, and sleepers).

Track failures or rail vehicle derailments represent approximately 50% of all accidents (AVANTE https://www.avantetech.com/news/avante-news/). The majority of track integrity problems are related to track geometry or gauge distortion, while the remaining problems are due to alignment, buckled tracks, and sub-soil erosion. On-board track geometry measurement systems provide a way to point out existing damage along the rail line in real-time and directly under the locomotive or rail vehicle. The mechanism of gauge widening is usually gradual and relatively long-lasting, but if it is not detected quickly, the final failure often takes place under the effect of some additional factor, such as exceeding

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the speed limit, poorly maintained and functioning running gear of a rail vehicle, the misalignment of rails, or extreme dynamical effects (such as high tractive forces).

Distinct technologies are used for urban rail transport. Urban rail transport systems are busy and can be serviced or diagnosed only when it is free (usually at night). The scientific literature deals with the questions of where the maintenance base should be located to maintain the urban rail transport infrastructure and what it should contain [1]. Another issue is the diagnostics of the railway infrastructure in the assessment of climatic features. When investigating the perception of railway specialists regarding the impact of climate change on railway infrastructure, it became clear that specialists have not sufficiently studied the impact of climate change on the railway infrastructure itself or on its maintenance and diagnostics [2, 3]. For railway infrastructure maintenance works planning, it is recommended to choose a time when the weather conditions are most favorable. This principle is very similar as it applies to agricultural work. Therefore, scientists are developing algorithms to optimize railway infrastructure maintenance works by adjusting to weather forecasts [4]. An important aspect is the integration of railway infrastructure technical requirements between national railways and EU community documents. In this regard, within the framework of international projects, attempts have been made to systematize and digitize information, thus improving the possibility of finding inconsistencies in norms [5]. The scientific literature examines the question of how to predict changes in freight and passenger volumes due to railway infrastructure diagnostic or maintenance works. Based on the actual condition of the railway infrastructure, it is estimated when and what works will be performed, the duration of the works is estimated based on this, and according to the duration, cargo and passengers are diverted to other modes of transport [6]. Research has been conducted on mathematical and decision-making models to improve the application of railway maintenance planning and scheduling. The literature was reviewed for information on decision support models related to railway maintenance planning and scheduling, and the results translated into a problem taxonomy [7]. Non-destructive techniques are gaining popularity among the available methods for assessing the condition of railway infrastructure, as they can overcome the main shortcomings of conventional methods, such as the trenching and visual inspection of track sections. The research looks at the use of ground-penetrating radar (GPR) technologies for the sustainable monitoring of railway infrastructure. The main conventional and non-destructive methods used for the maintenance of railway ballast materials are presented, with special emphasis on their sustainability. It also provides an overview of research methods for the use of the aforementioned technologies for railway infrastructure monitoring, including key studies conducted in the laboratory and real-world environments [8]. It offers a data-driven decision support system that integrates road condition forecasts with tactical maintenance planning and operational planning. The system recognizes prediction uncertainty using a Wiener process-based prediction model at the tactical level [9]. When assessing the state of the railway infrastructure, mixed assessment methods are applied. On the one hand, measurements and diagnostics are performed; on the other hand, a system for evaluating the significance of damages is methodically created, thereby generating a complex infrastructure assessment model [10]. The organization of railway infrastructure works can be optimized both at the global level (for the entire infrastructure) and in its individual components (e.g., the optimization of rail grinding or the ballast lining). Sancho, Braga, and Andrade describe special methodologies and algorithms for solving this problem [11]. An important issue is the integration of maintenance algorithms according to individual infrastructure areas, such as tracks, structures, power, supply, and signaling systems. Yoshida, Tanaka, et al. considered the creation of the priority system and the organization of a set of works [12]. Ribeiro, Nascimento, et al. examined the question of how railway infrastructure maintenance and development management systems affect environmental issues [13]. They examined how to create a financing system for infrastructure maintenance that promotes sustainable and environmentally friendly solutions. A promising direction of research is the interactive modeling of the maintenance systems of railway infrastructures.

Sometimes, this activity is called creating digital twins. Such modeling allows for predicting the consequences of applying one or another model of care [14].

The well-timed maintenance and alignment of railway tracks in admissible conditions are vital for the smooth and safe movement of rail vehicles [15]. Deprived track alignment can cause poor vehicle ride quality, wheel flange disruptive contact, flange climb, and even the derailment of rolling stock. Accurate horizontal track geometry (TG) is measured using a dedicated track recording vehicle or a full track geometry recording system mounted on an in-service vehicle [15, 16]. Typically, rail vehicle operators use the sensors mounted on the bogie of in-service vehicles to estimate the mean track alignment using optical or contact sensors.

These days, railway technical and technological systems are entirely complex. This complexity of the system is continuously increasing, pushing managers to better understand how the system behaves and what its influence over transport service quality is. It should be stated that without having a well-designed, properly organized and effectively working knowledge management system with respect to factors influencing railway service quality, even the best intentions would probably be useless.

In the UK, Saumil, Li, and Jun [17] provided a quite relevant summary of TG faults and suggested that it would be beneficial to move from a maintenance regime based on reacting to faults to a predictive maintenance scheme, but the details of how this should be done were missing. Currently, unattended geometry monitoring systems make many measurements. Nevertheless, the attended track geometry management system cannot predict track asset degradation but can exclusively monitor it. RI-AMS analyzes past TG measurements and models and predicts its deterioration. This is the oncoming stage in railway track maintenance planning. There is a need to develop models showing how tracks degrade over time to make better predictions of the remaining life of an asset or showing how long it might be before maintenance is required.

The server of the TG monitoring interface has to handle large volumes of data and process the data to provide reports of what is happening on the railway line. It should be possible to use the Organizational behavior management (OBM) collected data to determine if specific RI maintenance interventions have been successful. If the problem occurs again soon after, perhaps the last maintenance operation was not cost-effective. Such a case would require integrating information about maintenance activities during data processing. In addition to monitoring the degradation of railway infrastructure conditions from in-service vehicles and OBM data, it would be helpful to monitor the effectiveness of RI maintenance. Furthermore, it should be ascertained whether the RI maintenance operation solved the original problem and whether the solution was sustained. This means that automated processing should include access to a database containing records of where, what, and when maintenance took place.

Further, this study assesses the influence of track geometry monitoring on RI processing.

2. EVALUATING THE METHODOLOGY OF TG CONDITION MONITORING SYSTEM EFFECTIVENESS

Multiple-criteria decision-making (MCDM) has been one of the fastest-growing areas of operational research, as it is often realized that many concrete problems can be represented by several (conflicting) criteria. MCDM provides instruments for finding the best option among possible alternatives by evaluating multiple conflict criteria. Several qualitative and quantitative criteria may affect each other mutually, which may make the selection process complex and challenging [18, 19]. In many cases, the decision maker has inexact information about the alternatives with respect to an attribute.

Many researchers have not only studied MCDMs but also compared these methods with each other. Mahmoud and Garcia [20] compared five MCDMs: weighted average, PROMETHEE II, compromise programming, ELECTRE II, and analytic hierarchy process (AHP) [20]. The consistency of the obtained results, the clarity of the methods, and the amount of additional information required for the method should be assessed. It was concluded that the weighted average method is the most suitable for solving their formulated task. Zanakis et al. [21] chose eight MCDMs for mathematical experiments: EL

ECTRE, TOPSIS [22], method of exponential weighting, interactive simple additive weighting, and four versions of AHP [21].

Since the selection of the optimum maintenance strategy for each piece of equipment is a vital decision for managing companies, many studies have been devoted to this area. Andrade and Teixeira [23] presented a review of some basic decision theory concepts and discussed their applicability in the selection of maintenance strategies. Jovanovič, Božovič, and Tomičić-Torlaković [24] proposed a method to find the criticality of each criterion dealing with maintenance strategies considering the simplification of the complex maintenance criteria presented a new approach for selecting the optimum maintenance strategy. They used game theory to make a decision when the customer (the receptionist of maintenance) wants to decide whether to have a service contract. The following discussion reviews some basic definitions of fuzzy sets that will be used throughout the deliverable. Let *X* be a classical set of objects, called the universe, whose genic elements are denoted by *x*. The membership in a crisp subset of *X* is often viewed as characteristic function μ_A from *X* to {0.1} such that:

$$\mu_{\mathrm{A}} = \begin{cases} 1\ if\ and\ only\ if\ X\ E \in A \\ \quad 0\ is\ otherwise; \end{cases}; \tag{1}$$

where (0, 1) is called a valuation set. If the valuation set is allowed to be the real interval [0.1], A is called a fuzzy set and denoted by A.

This study proposes a new approach for selecting the optimum strategy for railway infrastructure maintenance. This approach was developed based on the linear assignment method with some modifications. The authors aimed to develop a new approach that considers both quantitative and qualitative criteria when selecting a maintenance strategy and maintains interaction with maintenance experts. This interaction allows the maintenance experts to provide and modify their preference information gradually within the selection to make the results more reasonable. For this purpose, an interactive fuzzy linear assignment method (IFLAM) was developed and applied to choose the optimum RI maintenance strategy [25]. Firstly, after making a list of maintenance selection criteria, an expert committee is constituted to evaluate different maintenance strategies. There are various qualitative and quantitative criteria for maintenance strategy selection, and the expert team should screen out some criteria based on organizational goals and objectives. Ratings of each maintenance strategy under quantitative criteria, such as the mean time between failures and equipment costs, can simply be assessed and computed. The qualitative criteria rating of each maintenance strategy should be assessed by the expert team using linguistic variables. Every word in "IFLAM" is a concept that needs to be explored and understood before the method can be purposefully used:

1. Interactivity. Usually, researchers explore interactivity itself as the involvement of system users in the process of controlling its operation or as an indicator of two-way or multipartite feedback.
2. Fuzzy. Fuzzy methods refer to methods in which the values of the object or system assessment parameters are expressed not by a single numerical value but by a field of (usually three or four) values.
3. Linear. The concept of linear regularity is understood in mathematics as the first degree of proportionality—put simply, twice as much is twice as good. This concept (logical principle) in the name of the method separates the user of the methodology from the need to search for "hidden" extrema and brings about the condition that the extremum is at the end of the examined range of values.

Finally, the IFLAM is the most proper method for evaluating an RI condition monitoring system's influence on RI maintenance decision-making. This is because it allows both the evaluation of the technically (physical) measured values and the interpretation of parameter values as a subjective aspect.

3. ESTIMATION OF TRACK GEOMETRY QUALITY

Railway traffic or the intensity of using RI is another essential parameter influencing TG conditions. Traffic can be divided into three groups based on the deterioration factors: dynamic effects, speeds, and loads. Dynamic effects vary with the type of vehicle on the track, from heavy haul freight traffic to passenger trains and from fast passenger units to lower-speed mixed traffic. As a result, the track bed is subject to a wide range of bearing and bending stresses that may be imposed not only by the static mass of rail vehicles, their wheelsets, and their freight (loading) but also by dynamic actions, such as lateral (centrifugal) forces in curves, wheelset oscillation phenomena (creepage), acceleration, vibration, and irregularities on the rail running surfaces. As the speed increases, the dynamic forces significantly influence the deterioration of TG and reduce at low speeds. In Europe, three TQIs are proposed by EN 13848-5:2017 [26] to demonstrate track conditions and provide limitations to ensure railway system safety: the extreme value of isolated (local) damage, standard deviation over a defined segment length (typically 200 m), and mean value. These TQIs are applied to track irregularities such as longitudinal level, alignment irregularities, cross-level irregularities, and track gauge. Longitudinal-level irregularities are irregularities in the vertical direction and are defined as the mean value of both rails' vertical deviations from their nominal vertical position. Alignment irregularities are irregularities in the lateral direction, defined by taking the mean value of the lateral deviation of both rails from the nominal track center. Cross-level irregularities refer to the unintentional rotation of the track around its longitudinal axis, defined as the difference in height between both rails. Track gauge irregularity is defined as the deviation from the nominal track gauge, measured within 14 mm below the running surface at the smallest distance between the inside of the two rails.

The standard EN 13848-5:2017 [26] defines the three main levels for the classification of the value of the TQI:

I. Immediate action limit (IAL). IAL is the value that, if exceeded, requires measures to reduce the risk of derailment to an acceptable level. This can be done either by closing the line, reducing speed, or correcting the TG.
II. Intervention limit (IL). IL refers to the value that, if exceeded, requires corrective maintenance so that the IAL is not reached before the next inspection.
III. Alert limit (AL). AL refers to the value that, if exceeded, requires that the TG condition is analyzed and considered in regularly planned maintenance operations.

Performing RI condition-based maintenance and renewal actions during the life of the track should guarantee adequate track quality. It is crucial to understand the track geometrical degradation process over time [27]. The goals of this are to assist railway regulators in choosing which TQIs to apply and provide essential concepts to develop future TQIs. By creating or using suitable TQIs, railway regulators clearly understand track status, which is helpful in scheduling maintenance and inspection tasks and developing track degradation models. The ultimate goal is to attain a lower life-cycle cost at the system level, with high safety and availability. Seven superstructure TQIs identified in the literature review were applied to numerical analysis to examine the TQI characteristics further.

4. EVALUATION OF THE INFLUENCE OF TG MONITORING

In the first stage, the authors suggested evaluating the influence of rail infrastructure monitoring systems on different RIs considering their intensity of using railway networks and mainstream traffic speed. These parameters were included in the expert questionnaire as the parameters used to estimate the impact of RI monitoring systems. Seven experts in RI maintenance were proposed to perform this evaluation.

The guiding polemical inquiry for experts was, “What features are provided by applying track geometry monitoring?” The questionnaire formulated by the authors consists of four questions:

1) the reduction of overall expenses of TG measurement (inspection) due to system usage in in-service trains instead of track geometry recording cars;

2) avoiding the unnecessary occupation of railway lines due to a decrease in measurements with track geometry recording cars and a higher frequency of TG measurements due to system usage in in-service trains;

3) the steady safety of train operations due to prevention efforts to avoid critical (dangerous, risky) track damage (i.e., the timely identification of such damages to TG);

4) a more accurately planned and smoother process of RI maintenance by utilizing more efficient and continuous TG monitoring.

The response data of experts (respondents) were collected into one database, maintaining the same data structure that was created in the questionnaires. The values of the criteria weights are presented in

Table 1. The weights of the criterion indicate how important one aspect or another is in the operation of railways.

The data in Table 1 indicate that, according to experts, the second criterion (avoiding the unnecessary occupation of railway track stretches) is the most important. However, it is too early to draw final conclusions on this matter. The following is a collection of expert responses to the matter of how intensively the on-board track geometry monitoring system affects various aspects.

Table 1

Values of criteria weights

Criterion	The values of the criterion weights							
	Number of experts							Mean
	1	2	3	4	5	6	7	
1. The decreasing overall expenditures of TG inspection.	3	4	4	3	4	2	2	3.1
2. Avoiding the unnecessary occupation of railway track stretches.	4	4	3	5	5	4	3	4.0
3. High level of train traffic safety due to avoiding critical (dangerous, risky) track damages that are quickly identified.	5	3	5	3	4	2	4	3.7
4. More correctly scheduled and smoother RI maintenance process due to continuous TG monitoring.	5	1	3	4	4	3	3	3.3

An obvious feature of fuzzy methods is that both the criteria and the weights of the criteria are evaluated not by a single numerical value but by a group of numbers (usually three or four numbers, depending on the nature of the task). The survey process was simplified by having respondents assess both the weights of the criteria and the criteria themselves in a simple way (i.e., via a single-digit assessment). In the course of further research, these assessments were translated into the required form according to a simple methodology developed by the researchers. The values of the weights and the values of the criteria themselves were converted differently. The values of the weights were converted into the required form without difficulty. The value of the number given by the experts (1 to 5) was taken as an average (central) number, and the marginal numbers were calculated by subtracting or adding 1 (if the value of the number obtained did not fall within the range of 1 to 5, the marginal value of the range was used). The results of the translation of weight values into fuzzy form are presented in Table 2. An arithmetic mean was calculated for each row in Table 2. The transformation of the data in Table 2 into Table 3 is described as follows. Members of Table 2 zi,j (except for the left column, which is not part of the matrix) form the matrix Z. Matrix Z is then transformed into a matrix W, the members of which are wk,l (in this way, Table 3 is created, except for the left column, which is not part of the W matrix). A corresponding formula was created for each column W of the matrix.

For the first column of the matrix W (if l=1):

$$w_{k,1} = \frac{1}{7}\sum_{i=1}^{7} z_{(3k-2),i}. \tag{2}$$

For the second column of the matrix W (if l=2):

$$w_{k,2} = \frac{1}{7}\sum_{i=1}^{7} z_{(3k-1),i} \tag{3}$$

For the third column of the matrix W (if l=3):

$$w_{k,3} = \frac{1}{7}\sum_{i=1}^{7} z_{3k,i}. \tag{4}$$

This determines the generalized values of the weights. These values are given in Table 3.

The values of the weights and the values of the criteria themselves are converted differently. The values of the weights are converted into the required form without difficulty. The value of the number given by the experts (1 to 5) is taken as an average (central) number, and the marginal numbers are calculated by subtracting or adding 1. However, as indicated by the data in Table 3 (and as confirmed by the fuzzy technique), the second criterion (avoiding the unnecessary occupation of railway track stretches) is the most important for RI maintenance processing.

Table 2

Results of the translation of weights values into fuzzy form

Criterion number	**Criterion weighting (according to expert number from I to VI)**						
	I	II	III	IV	V	VI	VII
1	2	3	3	2	3	1	1
	3	4	4	3	4	2	2
	4	5	5	4	5	3	3
2	3	3	2	4	4	3	2
	4	4	3	5	5	4	3
	5	5	4	5	5	5	4
3	4	2	4	2	3	1	3
	5	3	5	3	4	2	4
	5	4	5	4	5	3	5
4	4	1	2	3	3	2	2
	5	1	3	4	4	3	3
	5	2	4	5	5	4	4

When summarizing the data in Tables 1 and 2, it should be emphasized that the data in v 2 is the result of the transformation of the data in Table 1. Fuzzy methods are special in that the data are not given in the form of one number but in the form of three or four numbers. The middle number (or the interval between the two middle number values in the case of four numbers) represents 100% of the respondent's acceptable value, while the edge numbers represent the compromise range of the respondent's acceptable values. An example of fuzzy data representation in the form of four numbers is shown in Fig. 1.

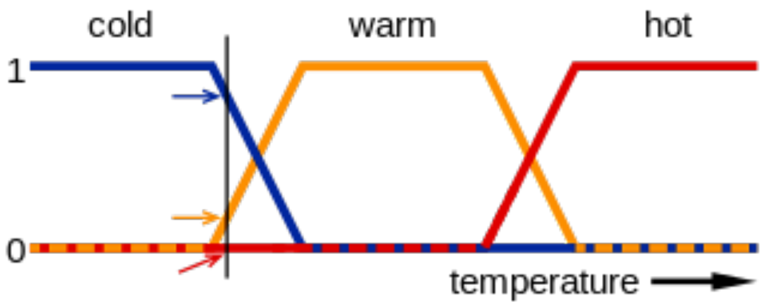

Fig 1. An example of fuzzy data presented in the form of four numbers

Fig. 1 shows a case of the classic Fuzzy problem, in which the respondents indicate which ambient temperature is too low, normal, and too high for them (in this study, the questions presented to the respondents were different). This is one of the first examples of applying the fuzzy data model, so it is often given as a typical example. The example shows three trapezoids. Each trapezoid has four corners and coordinates, and four numbers are used in the fuzzy data structure (a trapezoid can have one right angle, so two numbers can be equal). The four-number data format is used when respondents can accurately (objectively) describe their views on a particular issue (such as what temperature is suitable for them and what is too low or too high). When examining questions that are further away from the human body, the accuracy of the respondents' answers generally decreases. Therefore, using the four-number format makes little sense, and the three-number form was used. A typical example of this form is shown in Fig. 2.

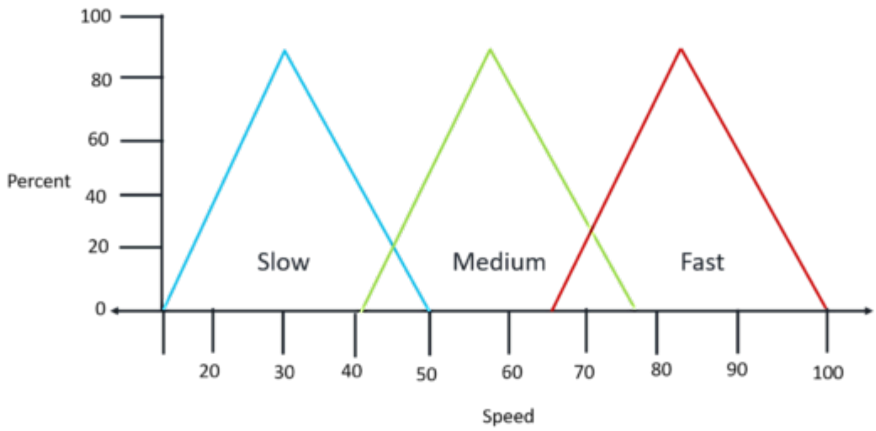

Fig. 2. An example of fuzzy data presented in the form of three numbers

In both Fig. 1 and Fig. 2, the vertical axes show the extent to which the respondent agrees with the statement presented (hot, cold, fast, or slow). The value representing this agreement can be a partial percentage or a fraction of 1.

Fig. 2 shows a typical example in which respondents are asked to estimate the speed of a vehicle (i.e., what is a slow, medium-fast, and fast vehicle). Since the speed of the vehicle is not felt as directly as the ambient temperature, the accuracy and objectivity of the respondents' answers are lower. Therefore, the form of the data is also different – 3 numbers. This study uses data in the form of three numbers (as shown in the example in Fig. 2). In order to convert the data into fuzzy form, the authors took the values from Table 1 as the middle number and obtained the other two numbers by adding or subtracting 1. Four-number fuzzy data can be used to obtain higher calculation accuracy. In this case, the larger it is impossible to calculate the accuracy since the accuracy is lost when the data are converted. Therefore, three numbers are enough for the fuzzy form. According to the data in Table 2, Table 3 is filled in based on Formulas (2), (3), and (4).

Table 3

The generalized values of the weights and criterion ranks

Criterion number	Weights in fuzzy form (three digits)			Average weight	Rank
1	2.14	3.14	4.14	3.14	4
2	3.00	4.00	4.71	3.90	1
3	2.71	3.71	4.43	3.62	2
4	2.43	3.29	4.14	3.29	3

The middle (colored) area of Table 3 presents the weight coefficient data in fuzzy form. The correctness of the conversion to fuzzy data could be checked (recommended) by checking whether the values of the "average of weight" column in Table 3 are proportional to the values of the "Mean" column in Table 1. When using other (not fuzzy) methods, the data from the "Mean" column of Table 1 can also be used as weighting coefficients. When using fuzzy methods, the data presented in the middle area of Table 3 should be used.

5. CONCLUSIONS

Each innovative railway track monitoring system is strongly focused on improving and harmonizing the proactive and interactive management of railway infrastructure. This investigation determined that an IFLAM is the most proper method for assessing a track condition monitoring system's impact on railway asset maintenance decision-making. Furthermore, an IFLAM allows the evaluation of both the technically (physical) measured values and the interpretation of parameter values as subjective features.

The authors suggest using fuzzy data in the form of three numbers to evaluate the performance of track monitoring systems. When data are presented in a different form, they should be transformed into the form of three numbers. Noticeably, considering the expert responses, the second criterion ("avoiding the unnecessary occupation of railway track stretches") is the most significant (weight value = 3.90; rank = 1) considering the influence on RI maintenance processing.

The third criterion ("high level of train traffic safety due to avoiding critical (dangerous, risky) track damages that are quickly identified") was identified as the second most significant (weight value = 3.62; rank = 2), considering the influence on RI maintenance processing.

When the significance of the criteria is known, it is possible to evaluate some means of rail infrastructure operation in a motivated manner. In this case, it is necessary to assess how significant the relevant measure is in relation to other criteria. Further, using the three-number form of fuzzy data is typically proper to evaluate the significance in order to maintain the validity of the method.

On-board track geometry monitoring is a great ground to shift from a time-based maintenance system of railway infrastructure to a condition-based maintenance system.

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