DYNAMIC SAFETY MANAGEMENT MODEL FOR RAIL TRAFFIC CONTROL

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Abstract – In rail transport, increasing emphasis has been placed in recent years on improving safety levels. Therefore, more requirements and legal documents require risk analyses to be carried out at various stages of investment implementation. One of the leading legal documents that introduce the obligation to monitor risk is Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety and Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on the common safety method for risk evaluation and assessment and re-pealing Regulation (EC) No 352/2009. Additionally, for traffic control systems, the requirements of CENELEC standards are mandatory.

These documents present the subject of safety level and show its relation with the safety targets defined in the railway system, including the different ways of measuring them. Methods are also available to analyse the safety level of railway system components in detail, both at the level of individual components, subsystems, and the whole national railway system. However, after conducting an in-depth analysis of the literature, the authors of the article indicate that these methods are not consistent with each other. There is no method defined to present the direct relation of the safety level of the components of the system on the achievement of safety targets for the national railway system. The research and analysis aimed to define an approach, a method that would meet all legal requirements but at the same time would allow to clearly and reliably determine the safety level of the railway system. To define a unified approach, the authors of the article propose to develop a model of a dynamic object - a railway system safety model, which has also been verified on accurate safety data in rail transport in recent years. This model organises the process of safety management on railways and allows to determine values influencing the achievement of safety targets on an assumed level.

Key words – risk; safety management; rail traffic control

JEL Classification – A33, C02, C15

INTRODUCTION

Successive modernisations of railway lines improve their operational parameters, but it should be remembered that safety is not treated as one of these parameters. The goal of investment safety is to achieve a measurable level of safety appropriate at a given time, which allows the statement that the investment ensures the level of safety assumed at a given time. Successive investments, in theory, are supposed to increase the safety level. However, as shown in this article, this is not a linear process. Expenditure on modernisation does not always translate (in the long term) into a proportional increase in safety and thus reduce external costs related to accidents. Therefore, the authors of this article undertook to establish a balance between increasing the exploitation parameters and increasing safety. However, to demonstrate such a relationship, tools for a holistic view of the railway system safety, examining the distribution of safety as a function of time are necessary. Such an innovative tool is the subject of research and is presented in this article.

The discussion about risks and the need for a method to assess them at various stages of investment is still very much alive on the railways. There are also numerous legal documents, which define the approach to risk and methods of risk

analysis, assessment and evaluation. Nevertheless, these documents often show divergent approaches to risk management, which causes ambiguity in the interpretation of requirements, especially by producers or managers. A uniform approach and precise requirements are critical to maintaining a high level of safety, which is closely related to achieving the sustainable development of rail transport. Therefore, in the article, the authors undertook to present a method that would unify the discrepancies in legal requirements and cover the entire rail system.

In the first part of the article, the authors focus on the unification of safety management in the formal and legal spheres. An in-depth analysis and comparison of existing standards are applied here, along with mapping individual processes. It is a critical issue because the lack of a uniform approach raises problems in assessing the global safety of a system.

In the following part of the article, the authors addressed the problem of time-distributed safety testing. Current methods focus on safety assessment statically. The paper proposes an innovative approach to risk management dynamically, using the theory of mechanics and automation. This approach is expected to lead to predictive risk management methods.

1. LITERATURE REVIEW

The formal and legal requirements for the safety of railway traffic control systems have been defined in a general manner Directive (EU) 2016/798 [5] and implementing acts as well as in the Technical Specifications for Interoperability (TSI), and in detail in the Commission Implementing Regulation (EU) No. 402/2013 [47], amending Regulation 2015/1136 [48] and CENELEC standards [49-50]. Since the entry into force of the provisions of the Directive, safety-related issues have been established at the level of the European Union by introducing common safety targets, requirements and safety indicators with the conditions contained in the TSI. In the safety considerations, the concepts of hazard and risk are commonly used. These terms are often used interchangeably, while their meaning concerning safety science is different. A hazard is a situation or action that can lead to an accident. However, the risk is defined in art. 3 of Directive 2016/798 means the frequency of accidents and incidents leading to damage (caused by a hazard) and the severity of the damage. We can express safety through the concept of risk. It is a state of no unacceptable risk of a threat materialising. The safety measures effectiveness in the system under consideration is expressed by the degree of risk reduction, and thus the effectiveness of risk management.

An important issue is also the common safety targets (CST) described in Directive 2016/798 on railway safety [5] and in the committee decision of 5 June 2009 [34]. Common safety targets means the minimum safety levels that are to be reached by the system as a whole, and where feasible, by different parts of the Union rail system. Another aspect is so-called national reference values which are indicators used to measure the achievement of CST. These values relate to the number of fatalities and serious critical injuries for the following groups of people, respectively: passengers, employees, users of level crossings, unauthorised persons on the railway area, other people and the general public. The level of NRV, as well as fatalities and weighted serious injuries for Poland, were determined and published by the national safety authority in an annual report [42]. The report shows that the assumed safety goals have been achieved in Poland - the actual value of the number of fatalities and serious weighted injuries did not exceed the assumed reference value for each group of people. At the same time, the results presented in the report indicated that the number of accidents involving railway workers should be remarkably reduced since this number is very close to the acceptable value (less than 3% below the acceptable value). For safety purposes also refers to ERA (European Union Agency for Railways) in the published guides [9, 8] in which it describes among others the value of CST and NRV and their impact on safety decisions. ERA also annually issues an assessment report on the achievement of safety targets, among others in the 2017 report [7], presenting the CST calculations for each Member State for the various risk categories. In addition, one of the few publications on CST is Article [35], which sets out the main CST and Common Safety Indicators CSI (Common Safety Indicators) based on the results collected during the implementation of European projects. One of the essential legislative solutions regarding the safety assessment of the railway system is introducing a common safety method for risk assessment (CSM-RA) described in Regulation 402/2013 [47]. This Regulation describes the safety assessment process for assessing the significance of a change. After analysing the available literature, it can be concluded that few documents or publications are devoted to the CSM-RA as one of the few documents that present a description of the use of CSM-RA in rail transport is [12]. In addition, article [12] shows the results of a comparative analysis of available source materials in terms of determining the method and level of implementation of EU risk management principles related to the introduced changes. One of

the documents that also presents the approach to CSM-RA is a guide issued by the European Railway Agency [10] and by the Office of Rail Transport [41]. This guide defines the basic concepts of risk and presents an approach to assessing the significance of the change.

In addition to regulations that define the approach to the safety of traffic control systems, there are also standards such as PN-EN 50126 [49] and PN-EN 50129 [50], which impose an obligation to carry out a risk analysis, which concerning design, production and operation of railway traffic control devices is an essential element. Standards indicate hazard identification methods, analysis of effects and probability of hazard occurrence and propose methods of risk assessment. However, risk assessment methods are only informative and relate only to matrix risk assessment methods. In addition, the proposed Hourglass model should be mentioned, which presents the entire process of the development of railway systems. About the methods of risk analysis in rail transport writes among others B. Leitner, in his publication [23], in which he presents a risk assessment model based on rail accident scenarios. Another approach using risk analysis methods such as FMEA, FTA is described by A. Berrado [2] and A. Morant Estevan [26]. Yet another approach to risk analysis is described in document [1], in which a so-called "intelligent system" was proposed for assessing the risk of rail safety using in fact fuzzy sets. The study of the above documents shows that there is no specific uniform approach to risk analysis, and there is a noticeable lack of universal methods of risk analysis and assessment in the railway industry. To carry out a risk analysis, you must first specify the risk factors, i.e. sources of hazards. Sources of hazards can be physical, chemical, biological, psychophysical, organisational, personal, and their presence, condition, or attributes are the source of the formulation of the hazard [16, 40]. The document [11] presents an absolute assessment method: "Evaluation of risk against a threshold". In this method, considered a whole method, estimation is obtained from the collision risk between aircraft through the modelling of the analysed system and confronting the obtained risk value against a pre-stipulated threshold value of risk (the Target Level of Safety - TLS). The system is considered safe if the estimated collision risk is not more significant than its threshold. In other words, its risk value does not exceed the threshold of safety for the system.

CENELEC standards base the approach to safety on systematic safety management and the creation of so-called safety case [30]. Standards define the process of risk analysis, hazard management, and specification and allocation of safety requirements. The above process is closely related to the determination of the Safety Integrity Level (SIL) based on the calculated THR (Tolerable Hazard Rate) [22], which is dedicated to electronic components and software. In addition, CENELEC standards provide a set of technical and organisational methods that should ensure that the required level of safety and reliability are achieved. Standard 50126 [49] mainly defines the requirements for RAMS (Reliability, Availability, Maintainability and Safety), in addition, the approach and methods used to evaluate the RAMS analysis are presented in documents [22, 25, 29, 27, 14]. However, the descriptions contained therein do not define CSM-RA and do not define a method for assessing the state of system safety.

The methods, tools and techniques proposed by CENELEC standards concern three levels of railway equipment applications: generic product (GP), generic application (GA) adapted to the specific requirements of a given railway market, railway undertakings, infrastructure managers, and specific application devices, so-called the specific application (SA) that is adapted to a particular location and a specific place in the field or a particular railway vehicle. Depending on the level of complexity of the system, PN-EN 50129 [50] indicates the possibility of developing a safety case at all levels of use or only on one. The entity responsible for the performance of the safety case is the manufacturer of the device or system at a given level of service: GP, GA or SA. Safety case is one of the essential documents regarding system safety and should contain evidence of the quality of management, safety management, functional safety and technical safety [22, 28, 36]. The safety case for modernised railways is presented in the doctor thesis [37].

The literature review shows two slightly separate approaches to railway safety management: an approach based on the common safety method for risk assessment (CSM-RA) and creating a safety case following CENELEC standards. There are many methods proposed for creating safety case based on agile management methods and GSN (Goal Structuring Notation) methodology [21, 38], as well as assessing the uncertainty of this approach [43]. The proposal to link the CMS-RA and CENELEC approach was made as part of a document drawn up by the European Railway Agency [10]. This work includes comparative analysis and common elements pointed out, particularly regarding the reference to the V model. However, a uniform approach to creating a safety case under the standard [50] and the CMS-RA method was not established. Only the usefulness of the use of safety case was generally determined. The attempt

to compile the CENELEC and CSM-RA standards was presented [15]. However, the juxtaposition was made on a rather general level. In the article, the authors present more detailed considerations on the relationship between these two methods. However, the primary problem is the lack of a unified approach to setting safety targets for the rail system and the related safety requirements for railway traffic control devices.

In addition, existing tools and regulations relating to risk management focus on minimising the risks in the immediate environment of the research facility, possibly optimising the measures needed to achieve the level of safety assumed. These methods are therefore reactive or, at best, proactive. However, there are no predictive methods, treating safety management as a process spread over time, having its inertia. In this article, the authors propose an approach to analyse safety management as a dynamic process.

The authors would like to draw attention to the possibility of applying the theory of testing dynamic systems to solve safety problems.

For this purpose, the authors propose using the model introduced by Roesser RP in [33] and developed by Kaczorek T. [18]. Roesser's model has been used to solve many industrial problems [6, 45]. Nowadays, this theory (in connection with Fornasini-Marchesini method) has become an important tool in engineering analyses such as process control, image processing, partial differential equation modelling, and thermal energy [19, 34].

2. THE PROBLEM OF DIVERGENCE OF LEGAL REGULATIONS

Safety case is defined in CENELEC standards [50] presented the use and the misuse of SIL in the railway domain. In addition, the standard describes the safety management process in more detail [13, 44]. The results of all activities carried out should be submitted in the safety case according to a strictly defined structure. The first part of the safety case requires a description of the system, consistent with the CSM-RA methodology. The second part is in the standards only and concerns the preparation of a quality management report. It is recommended to use quality management standards based on ISO 9001.

It should be noted that the application of appropriate quality management standards is an essential element in building a safety management system. In part three of the safety case, we can find the description of the safety management report. The common part of both methods is the use of hazard identification methodology and keeping a hazard log, as well as the process of determining safety requirements. In the standards, the requirements of

safety have been described more precisely, together with the division into types and with the method of allocating requirements to individual subsystems and components. The normative part four of the safety case contains the technical safety report. There you can find a detailed description of the methods of system analysis, testing, principles and conceptual solutions to ensure system safety. In addition, we will also see a description of the factors that should be considered when building a system. A detailed description of the creation and management of safety-related application conditions (SRAC), which according to the authors, relate to residual risk management, is also presented. In the CSM-RA approach, we won't find any mention of residual risk management, at least not so accurately. It can be assumed that the residual risk has been treated here by default and is managed through subsequent iterations of the risk valuation process, i.e. during the comparison with the risk evaluation criteria and determining whether the risk is acceptable. However, this is not sufficiently defined. Both in the standard and CSM-RA, it is difficult to reference the residual risk and the final risk assessment enabling linking the results of the whole process with the set safety targets. This difficulty lies in combining many factors affecting the state of safety and the quantitative interpretation of available data.

3. THE RESULTS OF COMPARISON DIVERGENT LEGAL REGULATIONS

The comparison presented in Table 1 shows that it contains all the elements required by the CSM-RA process.

4. THE DIVERGENCE OF LEGAL REGULATIONS DISCUSSION

After analysing the safety requirements set out in Directive 2016/798, Regulation 402/2013, TSI, CENELEC standards and other source documents, it can be concluded that there is a lack of a unified approach to managing safety targets and managing methods for achieving safety targets. In addition, the issue of appointing different entities performing safety assessment, i.e. assessment bodies (AsBo) and independent safety assessors (ISA), is not explicitly regulated. The benefits and methodology of ISA implementation are presented in the article [44]. These two entities currently operate in parallel and are established on separate terms. AsBo units must be accredited by the national accreditation body and the powers granted in one country remain valid throughout the European Union.

Table 1. Comparison of the safety case and common safety assessment method

CSM-RA	Safety case	
Definition of the system	System description	Part 1: System definition
-	Description of the quality management system	Part 2: Quality management report
The profiles of the assessment team	Safety Life Cycle	Part 3: Safety Management Report
	Safety organisation	
Safety plan	Safety plan	
Classification of the meaning of change	-	
Risk analysis	Hazard log	
Risk assessment		
Safety requirements	Specification of safety requirements	
-	System design	
	Safety checks	
Demonstration of compliance with safety requirements	Verification and validation of safety	
	Safety justification	
-	System handover	
	Operation and maintenance	
	Liquidation and disposal	
Safe integration	Ensuring proper functioning	Part 4: Technical safety report
	Effects of defects	
	Action on internal and external influences	
	Conditions of application related to safety	
-	Safety qualification tests	
	Part 5: Related safety cases	
	Part 6: Summary	

The role, importance and requirements for AsBo units are presented in the ERA document [17]. On the other hand, ISA units are established based on principles defined by each country separately, and their activities cannot be (directly) carried out in different countries. The latest normative [49] and legal [4] regulations are levelling these units together, but the actual implementation of these regulations has not yet occurred in the member countries.

5. THE PROBLEM OF DYNAMIC SAFETY MANAGEMENT

Tools and regulations relating to risk management have focused on optimising the measures needed to achieve the level of safety assumed. These methods are reactive or, at best, proactive. However, there is a lack of anticipatory methods that treat safety management as a staggered process with its own inertia.

To define these relations, the authors of the article propose a look at the safety of the railway system in the way dynamic objects are tested. This look would allow for a more efficient assessment of the current state of safety and predict this state's future and partial control of this state.

Whereby reference to the theory of dynamic objects covered in [24, 51] and the safety issues covered in [3, 32, 31] can be defined:
– rail system safety status - the smallest set that allows describing the level of system safety at any time,
– safety margin - the difference between the level of safety of the rail system expressed in quantitative or qualitative terms and the safety targets.

The model assumes treating the Safety Level, SL as a state composed of hazards h, probability p and an effect e and mitigation actions M(t). These are typical elements commonly used in risk assessment methods [43]. Mitigating actions are assumed to influence the level of safety.

Among the activities influencing the safety level, we can distinguish elements corresponding to mitigation actions, including the reliability of system components rate, quality of system components rate, subsystem manufacturing competence rate, subsystem maintenance competence rate, subsystem maintenance competence rate, risk management rate, operational work rate, safety-related contractual conditions rate, safety-related legal regulations rate,

control and supervision activities rate, system automation level rate. Under their influence, the level of safety changes and can therefore be attributed to the physical attribute of force or coercion. Minimising actions directly affect the study object, which will be a set of hazards in risk assessment. The number of identified hazards will indicate the complexity of the system and its size. The number of hazards identified indicates the complexity of the system and its size. The probability and effect (together constituting the risk) will affect the safety level in opposition to mitigating actions. The occurrence of probability and effect (risk) will counteract mitigating actions, suppress and repel them - counteracting a change in the object's position and thus change the safety level. Therefore, probability and effect in the assumed model will play the role of an elastic-damping system, which can be illustrated in Figure 1.
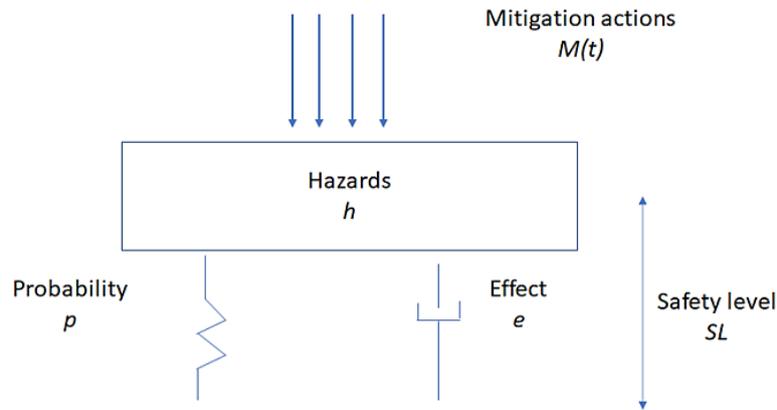
Fig. 1. Safety level model

Safety level as a measure of safety will be the inverse of CSI - the number of victims of railway accidents. The presented model should allow checking the influence on the SL safety level (and CSI) of minimising actions reducing the level of risk (of adequate strength), given the assumed number (mass) of hazards of specified probability and effect, considered as a process spread in time.

The use of the model should allow for a better understanding of the impact of subsequent (time-distributed) mitigation actions on the overall safety level of the system. It is therefore a prelude to predictive safety management.

6. DYNAMIC SAFETY MANAGEMENT MODEL RESULTS

Such a model can be described by the equations (1-3):

$$h \cdot \ddot{SL} + e(t) \cdot \dot{SL} + p(t) \cdot SL = M(t) \qquad (1)$$

from which, after substituting x1 for the SL safety level, the following relation can be obtained

$$\dot{x}_1(t) = x_2(t) \qquad (2)$$

$$\dot{x}_2(t) = -\frac{e(t)}{h} \cdot x_2(t) - \frac{p(t)}{h} \cdot x_1(t) + \frac{1}{h} M(t) \qquad (3)$$

In the next phase of the safety level analysis, we can try to determine the CSI, which is the inverse of the safety level and which can be related to the number of accidents through the relationship (4).

$$y(t) = -c \cdot x_1(t) + x_1(t_0) \qquad (4)$$

where: $y(t)$ - number of accidents per unit time; c - accident to safety ratio.

The theory presented in the description of the proposed 2-D dynamic risk model was verified using the statistics of accidents at level crossings. These statistics are shown in Figure 2.

We seek to relate the level of risk to the number of casualties at level crossings by fitting probability, effect and mitigation actions curve.

In further steps, the authors tried to select the values of functions responsible for curves h(t), e(t) and p(t) to achieve the best fit to the existing research object - the level of safety at railway-road crossings. Based on current research and available analyses [46, 20, 39], the number of threats h (for simplicity as a constant function) has been assumed at the level of 200, the effect function e as (random value) from the interval <8, 10> (a scale from 0 to 10 has been assumed, where 10 is the most significant loss, which is appropriate for railroad-road crossings), the probability

mapping function has been chosen from the interval <2,4> (a scale from 0 to 10 has been assumed, where 10 is equivalent to the probability of value 1. The low probability is due to the relatively small number of accidents concerning the number of train kilometres). The choice of mitigation actions curve M(t) also plays an important role. For the experiment, it was assumed that it would be a logarithmic curve, which is an approximation of the assumption that the mitigation actions in the initial phase are decisive - at the beginning, it is easy to introduce decisive actions. Over time, the introduction of new intense activities is more complicated. Nevertheless, the curve will depend on the currently observed phenomena and can be adjusted as needed in the future. Similarly, the value of e and p will also depend on time, which is related to changes in passenger-kilometres, the condition of the rolling stock, and the railway line condition.

Assuming the above assumptions, the course of the safety level, determined from relation (1), is presented in Figure 3.
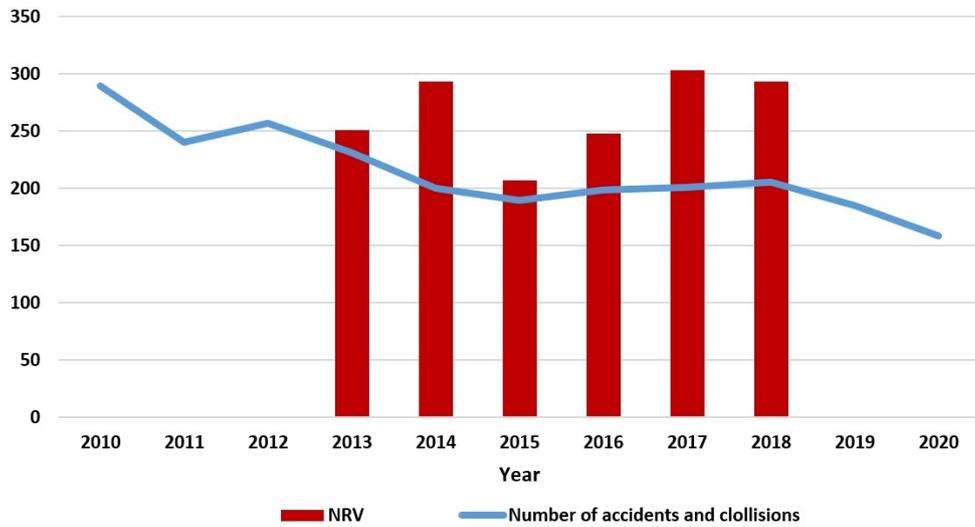
Fig. 2. Statistics on accidents and collisions at level crossings based on [52]
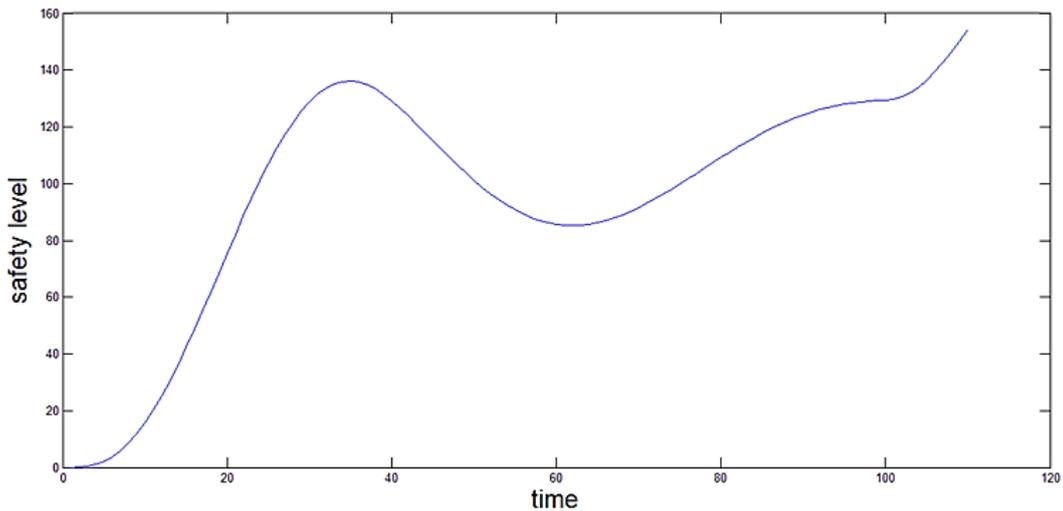
Fig. 3. Example of a safety level model result
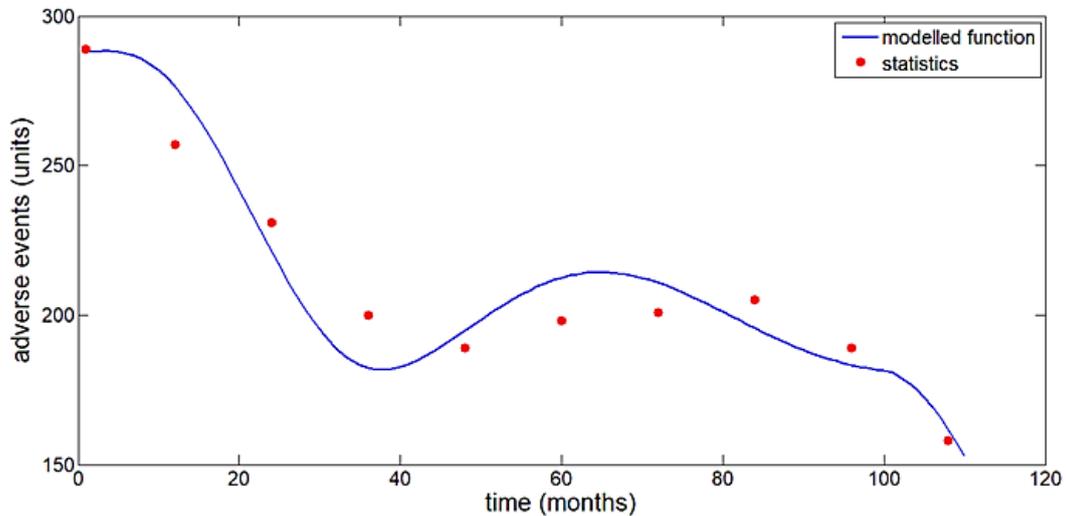
Fig. 4. Correlation of relations obtained from the model and statistical results

Then, to determine the CSI, it was necessary to invert the relation - to determine its negative value from relation (4).

As a result, a colleration of relations obtained from the model (4) and statistical results [52] was obtained, presented in Figure 4. As can be seen, the data from the model - marked with a solid line - are close to the actual data obtained from statistical sources [52] - whose values are marked with dots.

The developed model is an introduction to the problem of safety control, i.e. the transition in finite time to any specific safety purpose.

7. DYNAMIC SAFETY MANAGEMENT MODEL DISCUSSION

The model presented in this article presents safety management as a process spread over time. This is an innovative approach, as the analyses and risk assessment methods used so far have only raised the safety level statically, without considering the dynamics of the process, as shown, in literature review. These concepts will form the basis for further considerations on modelling railway safety in predictive way.

As a result of the tests, a railway system safety model was developed. The model organises the safety management process on the railway and allows the determination of values affecting the achievement of safety targets at the assumed level. In addition, the model can be used by various participants of railway investments, e.g. the investment contractor or the contracting authority. It is also worth pointing

out that for input signals, we can distinguish entities authorised to control them. In particular, they are the national safety authority, the ministry responsible for rail transport, as well as infrastructure managers and railway carriers.

Thanks to the application of the model, an approximation of the change in the level of safety at railway-road crossings has been achieved. It was shown that it has a character of a dynamic oscillating object.

The model has its limitations, among which one can point out the necessity of having a large amount of data both from analyses and risk assessments for the modelled object and the distribution of minimising actions. It is also necessary to have an appropriate research sample - evaluations performed over time. Similar experiments are planned for other railway statistics. Unfortunately, currently there is a lack of more detailed data, which could be analysed.

CONCLUSIONS

The analysis showed that the concepts related to risk in rail transport are not standardised. The article presents the concepts of risk in rail transport and presents a model for assessing the safety status of rail traffic control systems.

The article achieves a clear link between the different regulations describing risk management, which is of an implementation nature and can be used in the daily practice of railway companies and assessment bodies.

A proposal has also been made for a predictive method of risk management that treats this concept

holistically and in the time domain.

The article presents the problem of risk analysis in a dynamic system. However, the values of individual variables describing the state of the risk model have to be selected each time, using available statistical data.

The model presented in the article will be developed in further scientific work and will ultimately be used by various stakeholders during the implementation of investment processes, which may significantly improve the level of safety in rail transport.

This approach is innovative because it makes the risk assessment method dynamic, unlike the currently used static methods. This provides a prelude to the creation of strategies that predict safety (and risk) levels.

Work on a model for predictive risk management should be developed and continued. As a subject of continuing work to be further developed, the authors also propose to define the concepts of rail system safety achievability and safety stability, similarly to what has been covered in works on automation theory [18, 24, 51]:

– safety achievability - transition from the initial state of the rail system to a safer state, achieving by the system more stringent safety targets, using a series of minimising actions,
– safety stability - the ability of the rail system to maintain its safety targets after the change has been introduced.

DYNAMICZNY MODEL ZARZĄDZANIA BEZPIECZEŃSTWEM DLA STEROWANIA RUCHEM KOLEJOWYM

Dyskusja o zagrożeniach i potrzebie metody ich oceny na różnych etapach inwestycji jest wciąż żywa na kolei. Istnieje również wiele dokumentów prawnych, które określają podejście do ryzyka oraz metody analizy i oceny ryzyka. Niemniej jednak dokumenty te często pokazują rozbieżne podejścia do zarządzania ryzykiem, co powoduje niejednoznaczność w interpretacji wymagań. Co więcej, niejednoznaczne wymagania skutkują różnymi interpretacjami przepisów i ich różnym stosowaniem przez uczestników rynku. Jednolite podejście i precyzyjne wymagania mają kluczowe znaczenie dla utrzymania wysokiego poziomu bezpieczeństwa, co jest ściśle związane z osiągnięciem zrównoważonego rozwoju transportu kolejowego. Dlatego w artykule autorzy podjęli się przedstawienia metody, która ujednoliciłaby rozbieżności w wymaganiach prawnych i objęła cały system kolejowy.

W pierwszej części artykułu autorzy skupiają się na ujednoliceniu zarządzania bezpieczeństwem w sferze formalno-prawnej. Stosowana jest tu dogłębna analiza i porównanie istniejących standardów, wraz z mapowaniem poszczególnych procesów. Jest to kwestia krytyczna, ponieważ brak jednolitego podejścia stwarza problemy w ocenie globalnego bezpieczeństwa systemu.

W dalszej części artykułu autorzy poruszyli problem rozłożonych w czasie analiz bezpieczeństwa. Obecne metody koncentrują się na statycznej ocenie bezpieczeństwa. W artykule zaproponowano nowatorskie podejście do dynamicznego zarządzania ryzykiem, wykorzystując teorię mechaniki i automatyki. Oczekuje się, że podejście to zaowocuje wytworzeniem predykcyjnych metod zarządzania ryzykiem.

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