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APPLICATION OF AN IMPROVED BOWTIE METHOD IN A CSM-COMPLIANT RISK ASSESSMENT OF A CHANGE INTRODUCED IN THE EU RAILWAY SYSTEM

Summary. The issue of managing the risk associated with introducing changes to the railway system is very important from the point of view of safety management, as any change can significantly reduce the level of safety of a railway system. For this reason, such changes are regulated at the European Union (EU) level through a dedicated legal act known as the Common Safety Method for risk assessment (CSM). The example presented in this paper is a portion of the analysis carried out for an Estonian freight carrier with a bowtie method, which we improved so that it fully complies with the CSM requirements. This analysis concerns a change consisting of allowing the possibility of a freight train being driven by one person (with no assistant driver). The case study presented in the paper, although limited due to confidentially issues, allows a full description of how to use the proposed method in real-world applications.

1. INTRODUCTION

The management of risk associated with introducing changes is very important from the point of view of safety management, as any change can significantly reduce the level of safety. Therefore, although change management is crucial for counteracting accidents [1], it often receives less attention than it deserves [2]. In the case of railway systems in the European Union (EU), a special regulation has been issued to clearly describe the importance of managing risk that may result from changes. This regulation is called the Common Safety Method for risk assessment (hereinafter referred to as the CSM RA) [3]. It describes the procedure for proposing changes to the railway system and should be used by all actors that take part in the introduction of the change:

- railway infrastructure managers
- railway carriers
- entities responsible for the maintenance of railway wagons
- manufacturers of all types of technical facilities used in the railway system.

As reports from railway authorities established in various EU member states suggest, the regulation is not used as often as intended or is misunderstood [4–7]. This confirms the claim of Almklov [8], who pointed to problems in the transfer of safety science ideas to the practice of enterprises. Such problems

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could be related to the fact that legal texts mention the framework's application to risk management activities only but do not propose dedicated tools that could be used by companies. Of course, there are many recognised methods of hazard identification, such as Hazard and Operability Study (HAZOP), Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA), but their use causes problems with the required depth of analysis, among other issues.

In the project, which results are described in this paper, we solved this problem by proposing a modified bowtie method by considering the concept of broadly acceptable risk, which is specific to the CSM RA. The bowtie method is widely used in many areas of analysis, such as in the shipbuilding industry [9], gas pipelines [10], as well as in the transportation sector, including railways [11]. It is also widely described in scientific publications. De Ruijter and Guldenmund [12] reviewed articles indexed in the Scopus database that used different varieties of the bowtie method. Based on the analysis, they proposed a distinction between two types of this method:

- a quantitative method for diagrams used to calculate the probability of a top event and individual consequences, which are actually a combination of fault and effect tree analysis diagrams
- a qualitative method for diagrams whose main purpose is to present information in an understandable way.

The quantitative bowtie allows the use of various types of mathematical tools, such as fuzzy sets [10,13] or Bayesian networks [14,15]. In this way, it is possible to model, for example, human factors through relatively simple modifications of the probabilities of events depending on their vulnerability to human-related errors, as proposed by Targoutzidis [16]. However, the use of such ideas in practical risk assessment requires the development of dedicated computer software.

A qualitative bowtie is not used for calculations, but it can also play an important role in the risk assessment process. Diagrams can be used to draw risk pictures [18] or accident pathways [19], which significantly facilitate a mutual understanding of risk analysts. They show the range of impact of barriers (referred to in this paper as "safety measures," following the terminology used in the CSM RA) functioning in the explored domain. A comprehensive application guide of qualitative bowtie diagrams can be found in a publication by the Center for Chemical Process Safety and Energy Institute [17].

The aim of this paper is to show the application of an original qualitative variation of the bowtie method (described in detail in [20]). This is done by presenting a fragment of the analysis we carried out as part of a commercial project. The fragment was chosen such that non-disclosure agreement was not violated while showing how to identify hazards and assess their risk.

The rest of the present article is organised in the following way. Section 2 contains information about the materials and methods used (i.e. the background of the analysed change, basic information on the applied method and the risk model used for risk estimation and evaluation). Section 3 presents the selected results of the conducted analysis. In Section 4, the applied method and results are discussed and the conclusions are presented.

2. MATERIALS AND METHODS

2.1. One-man train operation in Estonia

The example presented in this paper is a portion of an analysis carried out for an Estonian freight carrier. The analysis concerned a change that allowed the possibility for a freight train to be driven by one person (with no assistant driver). This is a desirable situation in many countries worldwide but represented a significant change in Estonia. Before the project commenced, all passenger trains on Estonian railways were run by one person but always with another employee on board who is responsible for taking care of the travellers. If a hazard is activated, he or she can react, for example, by applying an emergency brake. An additional challenge for the risk analysis was the limited view the driver has from his or her cabin, as shown in Fig. 1.

(a) (b)

Fig. 1. The locomotive planned to be run by one person: (a) side view, (b) view from the driver's cabin

The subject of operating a train by only one person is described in the literature, mainly in relation to the situation of the railways in Australia [21,22] and in the London underground [23]. The research results described in those papers were used to formulate the causes of top events being explored, but it was necessary to take into consideration significant differences in the size of the railway network and the rules governing the operation of trains. This was achieved by analysing the railway instructions applicable in Estonia that are relevant to train operation. The expertise of the co-authors of this article helped achieves this objective.

The situation presented in the example (i.e. the signal passed at danger (SPAD)) involved a train passing without permission into the area marked with a stop signal (usually indicated with a red light). In this situation, several things can occur [24]:

- an accident at a level crossing due to the warning lights not being turned on
- derailment, perhaps caused by the train running off the tracks or by the movement of a switch under the rolling stock
- collision with another train on the same track
- workers on the track being hit and damage being done to equipment.

Research is being undertaken to reduce the number of such events by studying the behaviour of train drivers [25] and drawing conclusions from the analysis of large amounts of data [24].

2.2. The improved bowtie method

According to EN 31010, one of the basic methods of risk assessment is the bowtie method. This method is based on a visual and structural display of all possible scenarios for the development of events, from causes to events to the consequences of hazard activation. In a previous paper [20], we described an original improvement of a bowtie method defined in [17] that allows full compliance with the CSM RA. This description has been graphically summarised in Figure 2.

As with the standard bowtie method, firstly, all possible causes leading to the top event are identified. Then, the possible consequences of this event's occurrence are determined. It is important that all causes and consequences are independent of each other (i.e. each of the causes can lead to any consequence). The resulting diagram is supplemented with existing safety measures (marked in black), including measures to be removed as part of the change under consideration (marked with white and the dotted line). If these measures are important, escalating factors leading to the weakening of the effect of the safety measures may also be added to the diagram.

In the next step, the importance of all causes and consequences are analysed. Negligible causes and consequences (due to the probability of their occurrence or associated losses) are marked with green lines. This information is used in the initial classification of hazards identified as a combination of all causes with all possible consequences. Hazards that contain a cause or consequence marked in green are treated as hazards with broadly acceptable risk and excluded from further analysis. The risk of other hazards is estimated and evaluated with the help of a risk model.

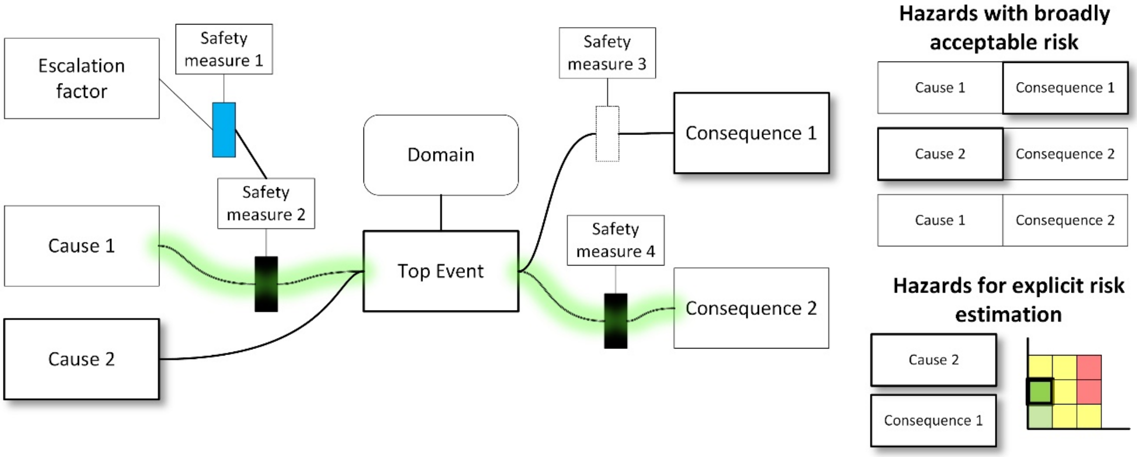


Fig. 2. Graphical summary of the improved bowtie method used in this study

If the risk evaluation indicates a risk that is higher than acceptable, meaning a method for reducing this risk should be proposed. Usually, such a method will involve the introduction of an additional safety measure, which is then added to the diagram and marked in blue. The results of the risk assessment carried out in this way constitute material for further consideration in the risk management process.

2.3. Risk model

In our study, we used the risk model currently in effect in Estonia for entities that perform vital tasks for the functioning of the state [26]. Until 2017, railway infrastructure managers and railway undertakings operating in EU member states were also covered by this regulation. Tables 1 and 2 present the definitions of meanings of particular probability levels and the effects of hazard activation. Figure 3 shows the risk model in the form of a risk matrix.

The five-level scale of determining the level of probability and the effects of hazard activation used in the regulation [26] is in line with the claims of van Duijne et al. [19], who pointed out that too many options cause the mere illusion of greater precision in risk estimation.

Table 1

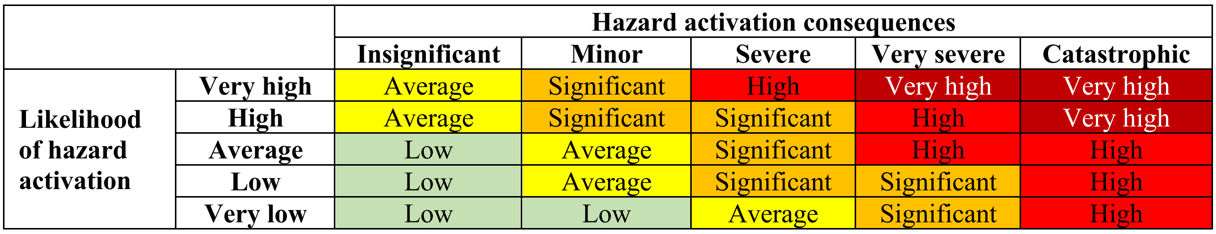
Definitions of the significance of individual probability levels used
in the risk model in accordance with [26]

Level	Meaning
Very high	> 99% probability Happens often. May happen within days or weeks
High	> 50% probability May happen easily. May happen within weeks or months
Average	> 10% probability Has happened before. May happen within a year
Low	> 1% probability Has not happened but may happen. May happen years from now
Very low	< 1% probability Probable only in extreme conditions. May happen once within 100 years

Table 2

Definitions of the significance of individual effects of hazard activation
used in the risk model in accordance with [26]

Level	Meaning		
	Extent of the provision of vital service	Reputation	Economic effect
Catastrophic	The provision of the service is hindered to the extent of 80–100% due to extremely severe interference with a critical activity	Extremely hostile constant attention from the public and the media, which lasts for several months	Decrease in planned income by > 30%; decrease in profit by > 30%
Very severe	The provision of the service is hindered to the extent of 50–80% due to very severe interference with a critical activity	Considerable negative attention from the public and the media, which lasts for weeks	Decrease in planned income by 20–30%; decrease in profit by 15–20%
Severe	The provision of the service is hindered to the extent of 30–50% due to severe interference with a critical activity	Recurrent negative attention from the public and the media, which lasts for days	Decrease in planned income by 5–10%; decrease in profit by 5–15%
Minor	The provision of the service is hindered to the extent of 10–30% due to minor interference with a critical activity	Negative attention from the public and the media, which lasts for days	Decrease in planned income by 1–5%; decrease in profit by 1–5%
Insignificant	The provision of the service is hindered to the extent of 0–10% due to petty interference with a critical activity, or there is no interference	Minimal or no negative attention from the public	Decrease in planned income by < 1%; decrease in profit by < 1%



		Hazard activation consequences				
		Insignificant	**Minor**	**Severe**	**Very severe**	**Catastrophic**
Likelihood of hazard activation	**Very high**	Average	Significant	High	Very high	Very high
	High	Average	Significant	Significant	High	Very high
	Average	Low	Average	Significant	High	High
	Low	Low	Average	Significant	Significant	High
	Very low	Low	Low	Average	Significant	High

Fig. 3. Matrix of the risk model according to [26]

3. APPLICATION OF THE METHOD

In Figure 4, we show a portion of the bowtie diagram developed for the top event (i.e. a train passing a signal at danger). The full version of the diagram could not be published due to confidentiality reasons.

The bowtie diagram in Figure 4 contains three of the 15 identified causes of the top event:

- no time to relax
- driving under the influence of alcohol
- wrong reception of a signal

In addition, Figure 4 contains all three identified consequences of a train passing a signal at danger:

- derailment
- collision with another rolling stock
- losses in railway infrastructure

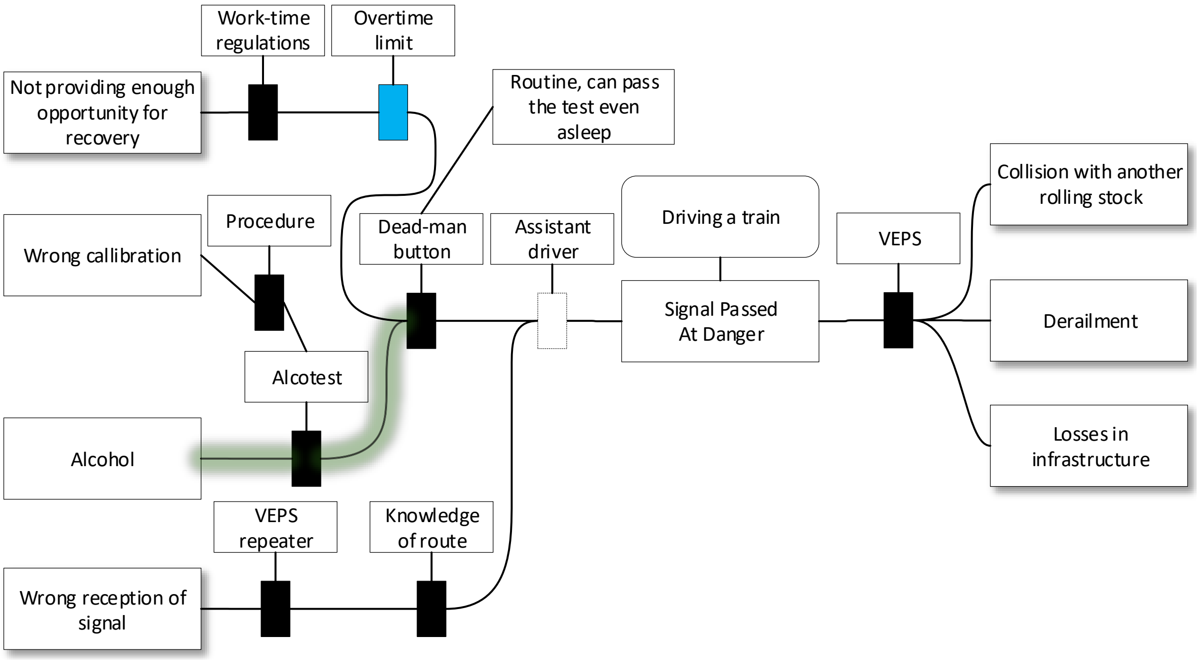


Fig. 4. A portion of a bowtie diagram for a top event of a train passing a signal at danger

Due to the method of securing level crossings in Estonia and the specificity of construction works on a network of single-track lines, we decided not to consider the remaining consequences mentioned in the literature [24].

Subsequently, existing safety measures were identified. Among the measures for controlling the causes of the top event, the following should be mentioned:

- regulations regarding working time, specifying the length of rest between successive shifts
- checking the sobriety of drivers before and after shift changes
- implementing a dead-man button (a system requiring periodic activity from the driver and implementing emergency braking in the absence of it)
- adding a repeater of signalling devices, which is a component of the VEPS train control system used in Estonia (electronic locomotive on-board signalling; Estonian: veduri elektrooniline parda signalisatsioon)
- ensuring drivers' knowledge of the route.

Of course, the safety function is also a function of the assistant driver, who controls the operations of the first driver and assists him/her, for example, in observing the signalling devices.

Escalating factors have also been observed to cause the deterioration of the safety measures:

- incorrect calibration of the breathalyser, which, however, is maintained in accordance with the manufacturer's instructions (safety measure of the escalating factor)
- automation of the use of the dead-man button (experienced drivers are able to push the button even while they are asleep).

The second of the above-mentioned escalating factors has no specific safety measure; however, the variable length of time between successive demands of the dead-man button in Estonia significantly reduces the possibility of an 'automatic' response by a driver.

The safety measure that allows for the complete elimination of the effect of the top event is the VEPS train control system, which, after passing the signal at danger, implements emergency braking. However, the operation of this system is limited to lines in which the ALSN system (continuous automatic train signalling; Russian: avtomaticheskaya lokomotivnaya signalizatsiya nepreryvnogo deystviya) is installed. This system does not include any stop signals other than light signals (e.g. signs or hand signals).

Among the causes and consequences of the considered top event presented in Figure 4, only one was considered by experts as associated with broadly acceptable risk. The sobriety control carried out twice during each shift means that the likelihood of a train driver being drunk is practically negligible.

Based on the information gathered, the hazards can be formulated. The hazards with broadly acceptable risk are listed in Table 3, and the remaining hazards, together with the results of the risk assessment and evaluation, are presented in Table 4.

Table 3

Hazards with broadly acceptable risk, identified as a result of the bowtie diagram exploration (Fig. 4)

No.	Hazard name
B40	Collision with another rolling stock caused by alcohol consumption after SPAD while driving a train
B41	Derailment caused by alcohol consumption after SPAD while driving a train
B42	Losses in infrastructure caused by alcohol consumption after SPAD while driving a train

Table 4

Hazards identified as a result of the bowtie diagram exploration (Fig. 4) with explicit risk estimation and evaluation

No.	Hazard name	Likelihood	Consequences	Risk category
H26	Collision with another rolling stock caused by not providing enough opportunity for recovery after SPAD while driving a train	High	Very severe	High
H27	Derailment caused by not providing enough opportunity for recovery after SPAD while driving a train	High	Very severe	High
H28	Losses in infrastructure caused by not providing enough opportunity for recovery after SPAD while driving a train	High	Insignificant	Average
H38	Collision with another rolling stock caused by the wrong reception of signal after SPAD while driving a train	Low	Very severe	Significant
H39	Derailment caused by the wrong reception of signal after SPAD while driving a train	Low	Very severe	Significant
H40	Losses in infrastructure caused by the wrong reception of signal after SPAD while driving a train	Low	Insignificant	Low

The risk level of two hazards, H26 and H27 (Table 4), was qualified as unacceptable (high). Both hazards were attributed to the same cause related to the lack of rest. Therefore, the experts participating in the exploration of this top event decided to introduce a new safety measure: a reduced overtime limit for train drivers carrying out their work without an assistant train driver.

As a result of the introduction of a new safety measure, the probability of the hazards considered has been reduced to the low level, and the level of risk has been reduced to the acceptable level of average. The presented risk assessment method reduced the risks associated with all identified hazards to acceptable levels.

4. DISCUSSION AND CONCLUSIONS

Maintaining a high level of rail transport safety in the EU would not be possible if rash changes were made to rail systems. This obvious principle is further strengthened by the provisions of a dedicated legal act – the CSM RA [3]. This act contains a risk management framework, which is widely accepted, but must always be augmented with more detailed tools for identifying hazards. These hazards' risk levels must also be estimated and evaluated. This task can be difficult for practitioners for whom safety science is not the main area of interest.

According to Aven [18], the risk identification process should be a creative process in which an attempt is also made to identify unusual events that may rarely occur in the analysed area. As in many other cases, the 80-20 rule applies to risk identification. This means that it takes 20% of the time to identify 80% of hazards (events or conditions that we know or have experienced), while the other 80% of the time is spent thinking of the other 20% of hazards (unusual and unexpected events). The process of searching for these rare events is called abductive reasoning [27], which can be understood as a 'process of noticing an anomaly and getting an explanatory hunch'; by means of abduction, a new idea (or hypothesis) is brought up from the region where 'all things swim' [28].

When exploring the hidden knowledge of the analyst or expert and stimulating their thinking, it is very important to adopt a systematic and structured method of risk identification. Top-down and bottom-up techniques, or a combination thereof, are used here to ensure comprehensive analysis. On the other hand, the use of complex methods when the scale or context of the problem does not require it is unjustified. Standards concerning railway communication and traffic control systems (e.g. EN 50129) clearly indicate that 'methodologies which generate an unrealistically large number of mostly trivial or imprecisely defined hazards are often a waste of resources'. Moreover, such an approach may result in misleading or unproductive risk analyses.

This is the situation we encountered in the initial phase of the project described in this paper. We attempted to apply a standard fault tree analysis method, but it was too specific for such a complex area of analysis. In addition to the workload needed to obtain the results of this analysis, other weaknesses were revealed, such as limited comprehensibility for people at different levels of the organisation. Therefore, we used qualitative or semi-quantitative methods. We took into account their main advantages, particularly the involvement of employees at all levels and the ease of understanding and using them.

In our opinion, the bowtie method is best suited for processing the identification of risks related to the operational changes in a railway. This is mostly due to the use of logical diagrams, which we consider the most transparent method for drawing a risk picture. Owing to different colouring schemes, it is easy to denote safety measures that did not exist before but were added specifically for maintaining the required level of risk after the change is introduced. In addition, we modified the standard bowtie method so that it makes full use of all possibilities described in the CSM RA [3] – in particular, its concept of broadly acceptable risk, which does not need additional analysis.

In conclusion, the bowtie-based method supplemented by CSM RA-relevant elements presented in this paper seems to be a good and relatively easy-to-use tool for identifying hazards. We have used it several times in projects involving the implementation of the processes described in the CSM. Of great importance for practitioners, the safety documents produced with the help of the described method have been positively assessed by a relevant assessment body, and the changes have already been introduced in practice.

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