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APPLICATION OF ROOT CAUSE ANALYSIS TECHNIQUES TO ENHANCE PASSENGER SAFETY DURING BOARDING ONTO MULTIPLE-UNIT ROLLING STOCK

Summary. *Applying the Ishikawa and the Bow-Tie techniques to identify root causes in a real-life passenger injury case while boarding a suburban train is examined, the effectiveness of existing control measures (barriers) is analyzed, and new ones are proposed in the article. The issue of enhancing passenger safety in suburban railway transport remains relevant despite the general downward trend in the number of railway incidents in Ukraine. Following signing the Association Agreement with the European Union, Ukraine undertook obligations to implement European standards and practices, including those related to risk assessment and the investigation of railway incidents as part of the overall risk evaluation process. However, the techniques for identifying root causes, as defined in ISO 31010:2019, have not yet been implemented in forensic expert practice or official and technical investigations. A real railway incident that was previously subject to forensic examination – a case of passenger injury during boarding an electric multiple unit train is analyzed in this study. Root causes and the central event – trapping the passenger's limb by the train doors – were identified using techniques provided by ISO 31010:2019. The paper outlines the application areas for these techniques and presents a comparative analysis. Potential consequences of the central event were examined, along with the existing barriers between root causes and the central event, and between the central event and its consequences. New barriers aimed at mitigating the effects of the central event are proposed. The scientific novelty of the research lies in the application of European approaches to root cause identification of railway incidents, which had not previously been applied in domestic expert or investigative practice. The practical value of this study is in demonstrating the introduction of new root cause analysis techniques into forensic practice and certified forensic methodologies. Further research should focus on applying ISO 31010:2019-compliant root cause analysis techniques to other types of railway incidents, such as derailments,*

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rolling stock collisions, and strikes involving vehicles or pedestrians, as well as on the use of additional techniques outlined in ISO 31010:2019 to enhance railway safety.

***Key words**: risk, traffic safety, multiple unit rolling stock, passenger, injury, investigation, Ishikawa diagram, Bow-Tie technique.*

1. INTRODUCTION

The implementation of European regulations in the field of railway transport in Ukraine requires, among other things, compliance with the requirements of risk management standards [1, 2]. Standard [1] defines the general principles of organizational risk management. Standard [2], in turn, regulates the application of various techniques (groups of techniques) depending on the stage of the risk management process, from establishing the scope, context, and criteria, through risk assessment and treatment, to the reporting stage.

Each of the techniques described in Standard [2] has its strengths, limitations, and a specific application area. Standard [2] classifies all techniques (groups of techniques) into ten categories: expert opinion elicitation techniques; risk identification techniques; techniques for determining sources, causes, and risk drivers; control assessment techniques; consequence and likelihood analysis techniques; dependency and interaction analysis techniques; risk quantification techniques; risk significance evaluation techniques; risk-based decision-making techniques; and risk recording and reporting techniques.

The research presented in this article is a logical continuation of the studies outlined in [3], which highlighted the challenges of applying European standards for risk assessment and cause identification of railway incidents in Ukraine.

This paper focuses on applying techniques for determining sources, causes, risk drivers, and strategies for analyzing control measures. The lack of widespread application of such techniques in domestic risk management practices within the railway sector justifies selecting these techniques. This direction is novel in the context of railway safety and, in our opinion, requires further promotion and integration into the risk management system of JSC "Ukrzaliznytsia".

2. STATEMENT OF THE PROBLEM AND RELEVANCE OF THE STUDY

Although railway transport remains one of the safest modes of transportation in Ukraine, the number of accidents is still high. According to data from the State Service of Ukraine for Transport Safety (Ukrtransbezpeka) [4], there were 451 accidents and 213 incidents on Ukraine's railways, resulting in 187 fatalities and 118 injuries in 2024. One of the approaches to reducing accident rates and personal injuries in railway transport is the prevention of railway incidents through analyzing past events. In our opinion, insufficient attention is currently paid to this issue.

In most cases, official and technical investigations of railway transport incidents (RTIs) and forensic railway examinations focus primarily on identifying the causes of the incident and the individuals whose actions or inactions were linked to the RTI. Issues of prevention and providing recommendations to avoid such events in the future are often either not addressed at all or only superficially [5].

Additionally, the analysis of control measures – the barriers that should have prevented the incident or mitigated its consequences – receives inadequate attention.

In contrast to long-distance passenger wagons, where conductors are present at the doors, multiple-unit trains typically lack staff at the doorways, and the doors close automatically. As a result, incidents frequently occur involving train movement with doors still open or limbs of passengers being trapped by closing doors, followed by train departure. Such situations can result in injuries to the passenger's limbs or, in the worst-case scenario, dragging of the person by the train, potentially leading to fatal consequences if the individual falls under the wheels.

The aim of this study is to enhance passenger safety during boarding onto multiple-unit rolling stock by improving techniques for identifying root causes of injuries occurring during boarding, with a view to their prevention and to increasing the effectiveness of existing control measures (barriers) intended to prevent such events.

The following objectives have been defined to achieve this aim:

– to justify the selection of the proposed risk management techniques for identifying the root causes of the analyzed case;
– to analyze the circumstances of passenger injuries using a real-world example;
– to identify the categories of causes and root causes that led to the main event "passenger injury";
– to determine the limitations of the Ishikawa technique and propose ways to address them;
– to define the central event for the Bow-Tie technique;
– based on the constructed Ishikawa diagram, to identify the causes and consequences of the central event;
– to analyse the system of existing proactive and reactive barriers from causes to the central event and from the central event to consequences, to propose new barriers, and to suggest ways to improve existing ones;
– to conclude and formulate recommendations and directions for further research.

3. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

To identify sources, causes, and risk drivers, Standard [2] recommends, among other techniques, the use of the Ishikawa technique [6]. The Bow-Tie analysis technique may be applied [7, 8] to analyze control measures (barriers).

The following publications support the potential of these techniques for the outlined purpose.

In [9], the authors emphasize the existing vulnerabilities in railway safety and accident prevention systems. Using the Ishikawa diagram, they conducted a comparative analysis of public railway accident databases from the USA, Canada, the European Union, and Mexico. The article justifies the need for a standardized classification of accident causes. The model proposed by the authors may serve as a foundation for improving safety management systems at the international level.

In [10], the Bow-Tie technique is applied to risk analysis related to operating freight trains by a single driver without an assistant. The authors highlight the importance of risk assessment in meeting European requirements, following [11]. The benefits of the technique are noted concerning analyzing rarely occurring events and identifying risks associated with operational changes in railway systems. A key advantage is the use of logical diagrams, which allow for clear visualization of the risk landscape and make it accessible to professionals from different fields.

In [12], the Ishikawa technique is applied to identify sources of risk related to brake system failures in freight vehicles. The authors identified contributing factors and proposed preventive measures.

A comparison between the Bow-Tie technique and Bayesian Network modeling is presented in [13]. The authors note the widespread use of the Bow-Tie technique for qualitative and quantitative risk representation. As further development, they propose an algorithm for converting Bow-Tie results into a Bayesian network, demonstrating the approach in a case study involving a mixing tank failure risk.

In [14], the Bow-Tie technique is integrated with text mining and fuzzy modeling to systematize causes and consequences of so-called "infrastructure intrusions" – the appearance of foreign objects (people, animals, vehicles) within the dimension gauge of rolling stock.

Thus, the Ishikawa and the Bow-Tie techniques have practical applications in leading countries' railway risk management systems. They continue to evolve through the refinement of the techniques and their integration with other techniques and approaches.

The Ishikawa technique [6] uses a team-based approach to identify root causes. All possible contributing factors are grouped into categories, the most common of which include:

– human factors (related to behaviour, knowledge, and skills),
– technical factors (malfunctions, design features, equipment quality), and
– organizational factors (processes, procedures, interdepartmental interaction).

The analysis results are presented as a fishbone diagram (also known as the Ishikawa diagram).

The main steps in performing the analysis are as follows:

– Define the event (effect) to be analyzed, which is placed at the "head" of the fishbone diagram;
– Achieve consensus on the main categories of causes. Typically (though not necessarily), categories such as Methods, Machines, Management, Materials, Manpower, Money, Environment, Equipment, People, Measurements, etc., are used. Additional categories may be added depending on the context.
– By sequentially asking questions such as "why?" and "how could this happen?", potential causes and influencing factors within each category are explored. Coordinated causes and factors are then added to the diagram branches;
– All branches are reviewed to ensure logical consistency, completeness of analysis, and relevance to the main event;
– The team identifies the most significant contributing factors.

The technique has strengths and limitations, as outlined in Standard [2], which must be considered when selecting it to analyze a specific situation.

Strengths of the Ishikawa technique:

– encourages participation and draws on collective knowledge;
– provides a structured approach to brainstorming and similar identification techniques;
– applicable to a wide range of situations;
– offers a clear, graphical representation of cause analysis;
– helps highlight environmental issues;
– can be used to identify factors contributing to both desirable and undesirable outcomes.

Limitations of the technique include:

– dividing causes into categories at the start may result in the underrepresentation of interactions between categories;
– potential causes not covered by the selected categories may remain unidentified.

Standard [2] recommends using Bow-Tie analysis for visualizing and presenting risk information in situations where a single event may have multiple causes and consequences. This technique is employed to study the causes and consequences of risk events and assess the effectiveness of control measures (barriers) at each stage, from causes to the central event and from the central event to its consequences.

It is assumed that effective control measures should support each path from a cause to the central event and from the central event to its consequences. It may include analysis of the potential failure of control measures and factors that either facilitate or hinder the occurrence of the central event and its consequences. The technique is considered a simpler alternative to more complex techniques such as Fault Tree Analysis or Event Tree Analysis, particularly when the event is more complicated than a simple linear chain but does not require excessive detail.

The technique can be used proactively – to model potential events – and retrospectively – to analyze events that have already occurred. Cascade analysis is also possible, where the consequence of one event becomes the cause of another.

The Bow-Tie diagram is often used to create a visual "risk passport," which facilitates engagement not only of analysts but also management, technical specialists, and other stakeholders.

The input data required to construct a Bow-Tie diagram include:

– causes of a predefined event;
– possible consequences of this event;
– control measures that may alter the course of the event or mitigate its impact.

This data may be derived from risk identification and control techniques (e.g., risk analysis, audits, checklists, etc.) or the expert experience of staff familiar with the processes related to the risk.

The result of Bow-Tie analysis is a clear diagram that illustrates:

– the main risk pathways – from causes to consequences;
– control measures already in place to prevent or mitigate the event;
– factors that could lead to control failure – including technical, organizational, or human factors;

- possible consequences following the event;
- post-event controls aimed at reducing harm or impact.

The Bow-Tie diagram serves the following functions:

- a risk communication tool in a simple and accessible format;
- a means of documenting all elements of the risk (causes, events, consequences, controls);
- a basis for developing response plans or improving the control system.

As with every risk management technique, Standard [2] outlines the strengths and limitations of the Bow-Tie analysis technique.

The strengths of this technique include:

- simplicity and visual clarity;
- ease of understanding and interpretation (it provides a clear graphical representation of the event, its causes, and consequences);
- focus on control measures;
- no requirement for a high level of specialist training.

The technique is accessible to various participants, including technical staff, management, and safety professionals.

Despite its simplicity and clarity, the technique has limitations. The Bow-Tie diagram is not well-suited to situations where the causes of an event are interdependent – that is, when multiple conditions must simultaneously be met for the event to occur – and it may oversimplify complex scenarios. In such cases, the Bow-Tie technique should be supplemented with Fault Tree Analysis (FTA) or Event Tree Analysis (ETA).

The procedure for analyzing the causes and consequences of a central event using this technique is as follows.

The event under analysis is placed at the central node of the Bow-Tie diagram (see Fig. 2). Risk sources (or hazards/threats in the safety context) are listed to the left of the node. They are connected to the central event by causal pathways. Each path's barriers (control measures) are shown as vertical blocks across the lines. To the right of the central event, lines are drawn from the event to each potential consequence. Vertical bars along these paths represent reactive control measures or barriers that mitigate the consequences.

Escalation factors – conditions that may lead to control failure – can also be added, along with escalation factor controls. Supporting management functions (such as training) that enable or enhance controls may be shown below the Bow-Tie diagram and linked to the relevant controls.

4. PRESENTATION OF THE MAIN MATERIAL

4.1. Brief description of the railway incident underlying the study

The basis of this study is a real railway transport incident whose circumstances are typical of cases involving passenger injuries during boarding. The description and selected conclusions from the forensic railway examination of this case are presented below (personal data of the individuals involved, dates, and names of infrastructure facilities are omitted to ensure confidentiality).

The incident occurred during the boarding of a suburban train, when a passenger suffered a severe injury: the upper right limb was amputated at the lower third of the upper arm by a wheelset of an electric multiple unit. This was classified as a grievous bodily injury.

The investigation established that the following sequence of events preceded the incident:

In accordance with applicable regulatory documents governing the dispatching of trains, the station duty officer prepared the departure route for the EMU and cleared the exit signal. This signal authorized the train to depart according to the timetable. Thus, upon reaching the scheduled departure time, the train driver could (and was obliged to) proceed without receiving an additional dispatch command from the station duty officer.

It was not possible to determine, by expert means, whether the driver announced door closure and train departure via loudspeakers, as no system existed to record the issuance of such announcements automatically.

The regulatory documents do not clearly define the required actions of the assistant driver during the dispatch of a train from an intermediate station, particularly regarding whether they should exit the vestibule to observe passenger boarding. However, in this case, the assistant driver acted in accordance with Clause 2 of the Local Instruction, which governs boarding supervision at terminal stations. He exited the vestibule and monitored the boarding process. Visibility of the train, passengers on the platform, and the injured person was ensured.

After being informed by the assistant driver that boarding was complete, the driver closed the doors and initiated train movement, seeing that the exit signal was clear.

The injured passenger, who was intoxicated, attempted to board the train at the moment the doors were closing. His hand became trapped in the lower part of the door. The size of the passenger's hand was comparable to the size of a gap potentially formed by the working travel of the end switch rods and deformation of the rubber seals, possibly along with a slight misalignment of the door leaves. In other words, it was technically possible for the door status indicator to show "closed" even while the hand remained caught between the doors.

The train began to move, and the passenger, losing balance, was pulled under the wagon and injured.

Further findings from the investigation include.

It was impossible to reliably determine the technical condition of the suburban train's door control system (or its components) at the moment of departure from the station where the incident occurred. Regulatory documents do not define specific criteria for a malfunctioning or inoperative state – for instance, the obstruction size that should trigger the system to signal that doors are not fully closed. In cases where the obstruction's dimensions are comparable to the permissible movement range of the switch rods and the deformation of rubber seals, it is technically possible for the door-closed indicator light to be lit while an object is still lodged.

It was confirmed that the door control system (or its components) functioned as intended in the presence of relatively large obstructions preventing complete closure.

Clause 3.1 of the Local Instruction regulating locomotive crew actions during train departures does not clearly require the assistant driver to exit into the service vestibule and observe passenger boarding through open doors at intermediate stations. This requirement applies only to departures from initial stations.

Since the station where the injury occurred did not have limited visibility and there was a technical possibility to stop the train in a way that ensured visibility from the driver's cab, the responsibility to supervise boarding in this case rested with the driver personally or, under the driver's instruction, with the assistant driver – with the driver remaining responsible for the assistant's actions.

The assistant driver exited to the vestibule and observed a white light near the station duty officer's post, which he mistakenly interpreted as a dispatch signal (whereas a green signal should have been displayed).

A reconstruction experiment revealed that the injured person standing in the position before the accident would also be visible if the end-of-train signal light is visible. Conversely, if the injured person is not visible, neither is the signal light.

The forensic examination concluded that both the actions of the train crew and those of the injured passenger failed to comply with applicable safety regulations. The passenger's behavior, including being intoxicated and attempting to board the train in such a condition, contributed to the incident.

4.2. Establishing the root causes of passenger injury using the Ishikawa technique

Based on the recommendations of Standard [2] and the previously described real-life railway transport incident that resulted in a passenger injury, an Ishikawa diagram was developed, as shown in Fig. 1.

The "head" of the diagram contains the main event – "passenger injury". The determination of cause categories, following Standard [2], was carried out through expert discussion involving the authors of this article, acting as an expert group. Consensus was reached on the following categories of causes: "traffic management", "railway personnel", "passenger", "environment", "infrastructure", "equipment".

Within each of these categories, specific causes contributing to the injury were identified. These causes are displayed on the corresponding "bones" of the diagram.

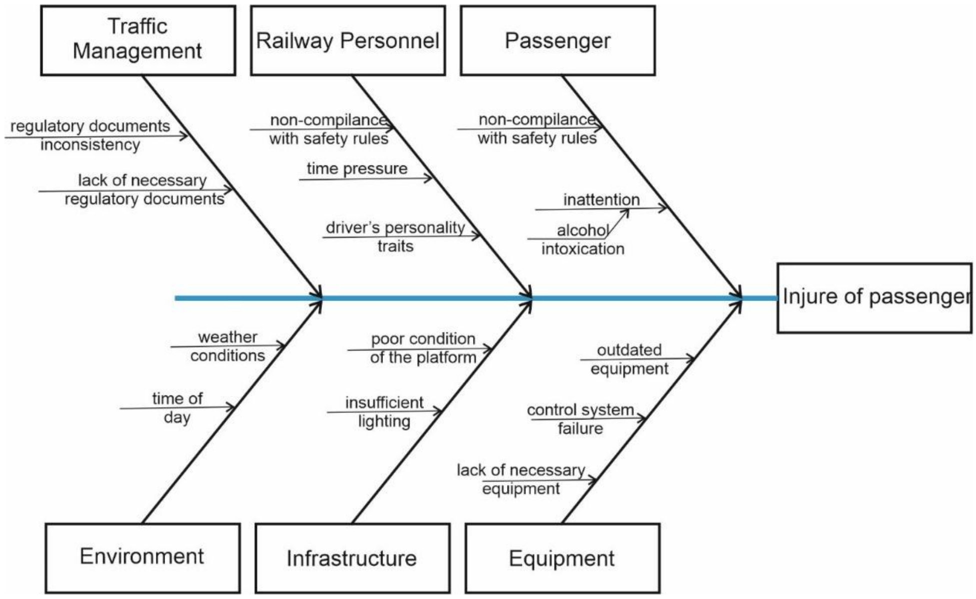

Fig. 1. Ishikawa Diagram for the Case of Passenger Injury

It should be noted that during the analysis and construction of the diagram, several limitations of the technique became apparent, some of which are also indicated in Standard [2]. Specifically, the diagram does not reflect the interactions between cause categories – for example, the relationship between gaps in the regulatory framework and non-compliance in the actions of railway personnel.

Moreover, the diagram does not explicitly represent one of the intermediate causes of the injury, namely, the trapping of the passenger's limb by the door. This event may directly lead to injury (in cases where the door-closing force is significant). It also creates a condition in which the passenger is compelled to move with the train, resulting in a fall and injury, either from falling onto the platform (a relatively less severe outcome) or under the train's wheels (a more serious scenario).

This is precisely why, during the barrier analysis using the Bow-Tie technique, the trapping of the passenger's limb by the door was selected as the top event, rather than the final injury caused by being struck by the train. The injury is only one (but not the only) possible consequence of the door entrapment.

4.3. Analysis of causes, consequences, and barriers using the bow-tie technique

Using the recommendations of Standard [2], a Bow-Tie diagram was developed to analyze the risks of passenger injury involving multiple-unit rolling stock during boarding.

Since injury caused by a train wheel is not the only potential consequence of a passenger's limb being trapped in the door of an electric multiple unit, the central event was defined as "limb entrapment in the door of multiple-unit rolling stock." The Bow-Tie diagram for this case is shown in Fig. 2.

The following risk sources (highlighted in grey) were identified:

– gaps in the regulatory documentation system (including inconsistencies among current documents and the absence of necessary regulations);
– non-compliance of actual railway staff actions with regulatory requirements during train dispatch and passenger boarding supervision;
– non-compliance of passenger behaviour with boarding regulations;
– time constraints due to short stops of multiple-unit trains;
– specific behavioral patterns of certain drivers who attempt to create a time reserve by departing as soon as the proceed signal is displayed, without waiting for the scheduled departure time;
– poor condition of the boarding platforms, which increases boarding time;
– insufficient or poor lighting during hours of darkness;
– technically and morally outdated equipment (such as doors and their control systems);
– loss of operability in door monitoring systems.

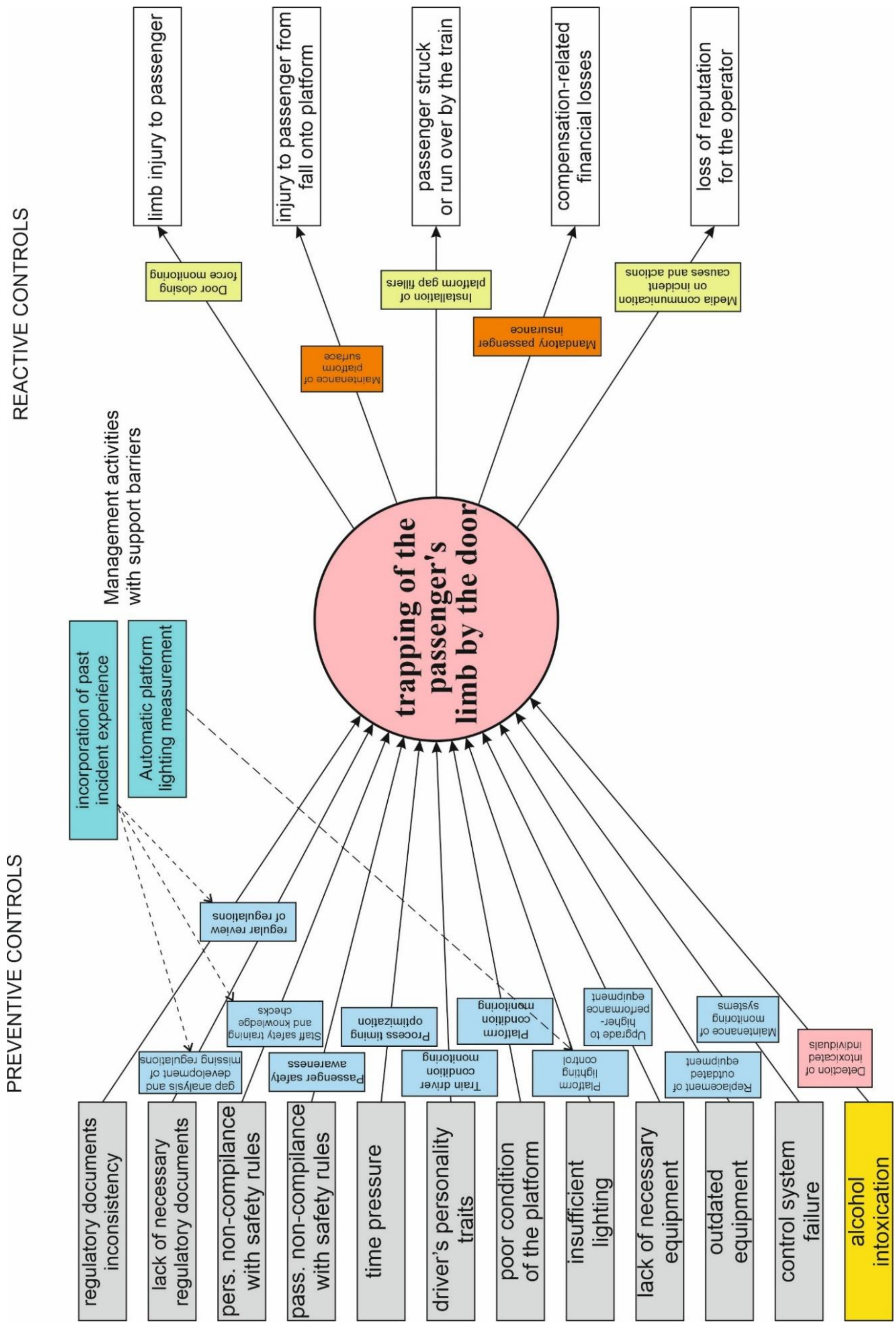

Fig. 2. Diagram for the case of a passenger`s limb being trapped in the door of an electric multiple unit

The escalation factor in this case was the passenger being under the influence of alcohol (highlighted in yellow).

For each risk source, barriers (highlighted in blue) were identified. A control measure was also defined for the escalation factor (highlighted in pink).

The consequences for the passenger were defined as:

– injury to a limb caused by door entrapment;
– injury resulting from falling onto the platform (without falling under the train);
– injury resulting from falling under the train (typically causing traumatic amputation and fatality).

In addition, the railway undertaking may suffer negative financial and reputational consequences.

Along the path to these consequences, barriers are placed to prevent or mitigate their impact.

Existing barriers are shown in orange. Barriers that are not currently implemented, but which the authors believe could be adopted in practice, are shown in yellow.

Among these, particular attention is drawn to technical solutions for platform–train gap fillers, such as those illustrated in [15]. Another innovative measure for domestic practice is proactive media communication, aimed at explaining the causes of railway incidents, informing the public about preventive actions taken by the railway administration, and supporting affected individuals.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

This study is based on a real case of serious passenger injury caused by the entrapment of a limb in the door of an electric multiple unit during boarding.

In analyzing this real-life case, the selection of the Ishikawa technique and the Bow-Tie technique was justified for identifying root causes and improving the system of active and reactive barriers – measures which contribute to enhancing passenger safety. The root causes of the injury were identified and grouped into categories. The central event (passenger’s limb being trapped in the door) – situated between the causes and consequences of injury – was also defined. The effectiveness of existing barriers was analyzed, and recommendations for their improvement were proposed.

The analysis of this case enabled the identification of root causes that lead to passenger injuries while boarding multiple-unit rolling stock and the evaluation of preventive and reactive barriers.

One of the main limitations of the Ishikawa and Bow-Tie techniques identified during the analysis was their inability to reflect interactions between causes in complex cases. This highlights the need to strengthen these techniques by incorporating Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) elements.

In the course of the reactive barrier analysis, it was found that specific control measures are not currently applied in domestic practice, including:

– monitoring the door closing force to prevent excessive pressure on passengers;
– installation of platform–train gap fillers;
– proactive media communication to inform the public about preventive actions taken by the railway administration and to provide support for affected passengers.

Future research directions include the feasibility analysis of applying other risk management techniques to this case, including:

– full implementation of FTA and ETA, and
– use of AcciMap, which enables a comprehensive assessment of risks and identification of causes of railway incidents, including organizational and financial factors.

These techniques will allow for identifying causal links and interactions between contributing factors at various levels, which cannot be achieved using the Ishikawa and Bow-Tie techniques alone.

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ЗАСТОСУВАННЯ МЕТОДІВ ВИЗНАЧЕННЯ КОРЕНЕВИХ ПРИЧИН ДЛЯ ПІДВИЩЕННЯ БЕЗПЕКИ ПАСАЖИРІВ ПРИ ПОСАДЦІ У МОТОРВАГОННИЙ РУХОМИЙ СКЛАД

Анотація. *У статті розглянуто застосування методу Ішікави та методу “краватка-метелик” для встановлення корінних причин реального випадку травмування пасажира під час посадки у приміський поїзд, аналізу ефективності контрольних заходів (бар’єрів) та розроблення нових. Проблема підвищення безпеки пасажирів у приміському русі актуальна,* *незважаючи на загальну тенденцію зниження кількості залізнично-транспортних пригод на залізницях України. Після підписання асоціації з Європейським Союзом Україна взяла на себе зобов'язання із імплементації європейських стандартів та практик, зокрема у галузі оцінювання ризиків та розслідування залізничних інцидентів як складової оцінювання ризиків. Однак поки що у судову експертну практику та у практику службових та технічних розслідувань методи встановлення корінних причин, які передбачені стандартом ISO 31010:2019, не впроваджені. У цій роботі проаналізовано реальну залізнично-транспортну пригоду, яка уже була предметом судової експертизи, – травмування пасажира під час посадки в електропоїзд. Встановлено корінні причини випадку та центральну подію, якою стало затиснення кінцівки пасажира дверима електропоїзда, із використанням методів, які передбачені стандартом ISO 31010:2019. Визначено сфери застосування цих методів та здійснено їх порівняльний аналіз. Проаналізовано можливі наслідки настання центральної події. Проаналізовано бар'єри на шляхах від корінних причин до центральної події і від неї до наслідків та запропоновано впровадження нових бар'єрів для зменшення наслідків центральної події. Наукова новизна дослідження полягає у використанні європейських підходів до встановлення корінних причин залізнично-транспортних подій, які раніше у вітчизняній експертній практиці та практиці розслідування залізнично-транспортних пригод не застосовували. Практична цінність роботи полягає у демонструванні впровадження нових методів встановлення корінних причин залізнично-транспортних пригод у експертну практику та в атестовані методики здійснення судових експертиз. Перспективами подальшого розвитку цих досліджень є застосування методів встановлення корінних причин, що передбачені стандартом ISO 31010:2019 для досліджень інших видів залізнично-транспортних пригод: сходів із рейок та зіткнень рухомого складу, наїздів на транспортні засоби та людей, а також застосування інших методів, що передбачені стандартом 31010:2019 для дослідження залізнично-транспортних пригод з метою підвищення безпеки руху*

Ключові слова: *ризик, безпека руху, моторвагонний рухомий склад, пасажир, травмування, розслідування, діаграма Ішікави, метод "краватка-метелик".*