Journal of Engineering Management and Systems Engineering
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Risk Management in the Transport of Dangerous Goods in Hungary: A Statistical and FMEA-Based Case Study on Bitumen Transportation

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Received: 10-20-2024 **Revised:** 12-01-2024 **Accepted:** 12-10-2024

Citation: Á. Drégelyi-Kiss, G. N. Tóth, A. Horváth, and G. Farkas, "Risk management in the transport of dangerous goods in Hungary: A statistical and FMEA-based case study on bitumen transportation," *J. Eng. Manag. Syst. Eng.*, vol. 3, no. 4, pp. 236–247, 2024. https://doi.org/10.56578/jemse030405.

Abstract: Risk management in the transportation of dangerous goods is critical for safeguarding human health, the environment, and infrastructure. This study explores systematic methodologies for risk assessment in the context of hazardous materials transit, with a particular focus on the transport of bitumen in Hungary. Key techniques, including Failure Mode and Effect Analysis (FMEA), Hazard and Operability Analysis (HAZOP), and Bow-Tie Analysis, are employed to identify, evaluate, and prioritize risks associated with the transportation process. These approaches enable the systematic breakdown of potential failure points, the evaluation of their effects, and the identification of mitigation strategies. The case study on bitumen transport highlights several significant risk factors, including operational failures, human errors, and vehicle-related incidents. The analysis reveals the importance of robust safety measures, such as enhanced driver training, real-time monitoring systems, and comprehensive documentation protocols, in reducing the likelihood and impact of such incidents. Furthermore, the study advocates for the continuous improvement of risk assessment procedures, emphasizing the need for adaptation to evolving regulatory standards and emerging challenges in hazardous materials transport. The findings underscore the importance of a proactive safety culture that integrates both technical solutions and organizational practices, ensuring a comprehensive approach to risk management in the transport of dangerous goods (TDG).

Keywords: Transport of dangerous goods (TDG); Risk analysis; Failure Mode and Effect Analysis (FMEA)

1 Introduction

The transportation of dangerous goods, including chemicals, flammable substances, and toxic agents, poses significant risks to human health, the environment, and infrastructure. As such, comprehensive risk analysis and risk assessment are essential components in managing the safe transit of these materials. These assessments involve identifying and evaluating the hazards associated with the transport of hazardous materials, as well as determining the probability and potential impact of accidental releases, fires, explosions, or contamination events.

By rigorously analysing these risks, organizations can establish preventative and mitigative measures tailored to the specific properties and behaviours of dangerous goods. Such measures range from appropriate packaging and labelling protocols to well-prepared emergency response strategies, all aimed at minimizing the likelihood of incidents during transit. Furthermore, risk assessment plays a crucial role in ensuring regulatory compliance with international, national, and local standards that govern the transport of hazardous substances. These standards mandate certain safety practices to reduce the potential for environmental harm and to safeguard public health, while also reducing the likelihood of legal and financial repercussions associated with non-compliance.

Beyond regulatory adherence, risk assessment in the context of dangerous goods transport underpins responsible resource allocation, directing attention and resources to high-risk areas. This targeted approach fosters a safer operational environment, mitigates costly post-incident liabilities, and enhances stakeholder confidence in the organization's commitment to safety. As a result, robust risk analysis and assessment protocols are indispensable to advancing a proactive culture of safety, accountability, and environmental responsibility in the transport of hazardous materials [1].

According to ISO 31000:2018 [2], risk is defined as the effect of uncertainty on objectives, which can be either positive or negative. This definition is particularly relevant in management systems, as objectives may encompass diverse aspects such as health and safety, environmental sustainability, and operational performance, and they may apply across various levels, including products, projects, processes, and strategic initiatives. Risk is often characterized in terms of potential events and their consequences, or a combination of these factors, and is typically expressed as the interplay between the likelihood of an event and the magnitude of its consequences. Furthermore, uncertainty is described as the partial or complete deficiency of knowledge regarding an event, its consequences, or the likelihood of its occurrence, underscoring the importance of adequate information and understanding in effective risk management.

Risk management involves coordinated activities to guide and control an organization's risk. The process comprises six stages (Figure 1). The first stage, establishing the context, involves defining external parameters, such as economic or environmental factors and trends influencing organizational goals, and internal parameters, which include the organizational environment and its objectives. Risk assessment, a critical phase, includes risk identification, analysis, and evaluation. During risk identification, the organization identifies sources, impacts, causes, and potential consequences of risks, resulting in a comprehensive list of risks that could affect the achievement of objectives either positively or negatively.

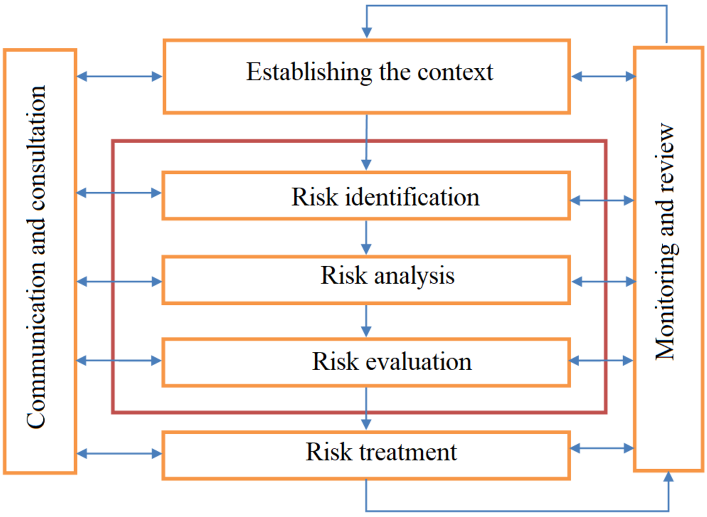

Figure 1. Risk assessment process

Note: This figure was prepared by the authors

In the context of transporting dangerous goods, it is crucial to identify, analyse, and evaluate risks due to the numerous potential hazards involved in the process. Several risk assessment methods are presented, particularly those that are universally applicable and effective in managing the specific risks associated with the transportation of hazardous materials. These methods aim to ensure safety, mitigate potential consequences, and enhance overall risk management practices in this critical domain.

Sustainability in transportation is critical for protecting the environment and ensuring human and ecological health without compromising our way of life. Sustainable transport balances efficiency, environmental protection, and safety, particularly in the movement of dangerous goods, which pose higher risks due to their hazardous properties. Dangerous goods include explosives, gases, toxic substances, and radioactive materials, among others, and their transportation requires strict adherence to international regulations. Accidents involving such goods can cause severe damage to the environment, infrastructure, and human life, often exacerbated by human error, inadequate training, and poor vehicle maintenance. Effective risk management, optimal route planning, and rigorous safety protocols are essential to mitigating these risks and minimizing socio-economic costs associated with transport accidents. Collaboration among organizations, enhanced training, and innovative methodologies for safety assessment play pivotal roles in addressing these challenges [3].

The FMEA method, originally developed by the US Military and later adopted by NASA and Ford Motors, is now widely used across industries as a systematic risk assessment tool [4, 5]. The AIAG and VDA harmonized their methodology and requirements in a 2017 handbook [6]. FMEA employs a hierarchical structure to identify potential failures in systems, subsystems, or components, analyse their causes and effects, and recommend actions to mitigate risks. It encompasses Design FMEA (DFMEA), Process FMEA (PFMEA), and Monitoring and System Response FMEA (FMEA-MSR), following a six-step process: scope definition, structure analysis, function analysis, failure analysis, risk evaluation, and optimization. PFMEA uses 4M analysis (Man, Material, Machine, Method) for structural and functional evaluations. Risk is evaluated based on severity (S), occurrence (O), and detection (D), with tables provided for determining action priorities. This collaborative approach helps systematically address failures, enhancing reliability and safety in various applications.

TDG poses significant risks to railway operations, particularly in mining-affected areas where infrastructure damage can compromise safety and operational efficiency. By applying FMEA [7], potential failure modes in TDG, such as leakage, spills, or derailments, can be systematically identified. The methodology assesses the severity of the risks, the likelihood of occurrence, and the ease of detection to prioritize actions. This structured approach enables the development of targeted mitigation strategies, such as enhanced inspection protocols, improved containment systems, and optimized route planning, ensuring the safe transport of hazardous materials while maintaining the reliability of railway services.

As an example, the risk assessment for braking systems [8], based on FMEA methodology, evaluates failure modes by combining severity (impact on people, property, and systems) with frequency of occurrence. Severity levels range from insignificant (minor injuries or system damage) to catastrophic (multiple fatalities or extreme environmental damage), while frequency values are categorized from frequent (occurring every six weeks) to highly improbable (extremely rare). The study identifies intolerable risks—such as frequent failures of brake actuators and pneumatic pipelines—as the most critical, requiring immediate risk control. Tolerable and negligible risks, while less urgent, are also considered. The findings prioritize mitigation strategies to address intolerable risks, particularly those with system-wide effects, such as brake actuator failures caused by wear, corrosion, and impurities, to enhance overall braking system reliability and safety.

HAZOP is a qualitative, systematic risk assessment tool [9] that uses guide words (e.g., "No," "Higher," "Reverse") to identify potential risks in processes, products, or systems. Originally developed for chemical processes, it has since been applied to other complex systems to prevent risks to people, equipment, and the environment, guided by IEC 61882 [10]. Bian and Wang [11] demonstrate that HAZOP is an effective method for identifying and analysing risk factors in railway dangerous goods transport, improving safety and operability by examining deviations in key stages of transport. Using yellow phosphorus as a case study, the analysis provides practical recommendations to reduce risks and enhance the safety and efficiency of railway dangerous goods operations.

The cause-and-effect analysis, or Ishikawa (fishbone) diagram [12], developed by Dr. Kaoru Ishikawa, is a tool used to systematically identify the root causes of a problem by categorizing potential causes and analysing their relationships, helping to resolve complex issues effectively. Li and Wang [13] identify risk factors in the domestic hazardous chemical's road transport using the fishbone diagram, analysing factors related to drivers, transport vehicles, hazardous chemicals, management methods, and environmental conditions. The study highlights key causes of accidents, including driver errors, vehicle technical failures, hazardous chemical properties, inadequate management, and adverse environmental conditions.

Fault tree analysis (FTA) and event tree analysis (ETA) are methods used to identify and analyse failures or accidents in complex systems, where FTA focuses on the hierarchical structure of causes and probabilities of failures, while ETA models' outcomes from an initial event to mitigate consequences [12]. Lasota et al. [14] analysed the risks in road TDG using FTA. It identifies key risk factors, such as non-compliance with ADR requirements, poor vehicle and infrastructure conditions, and improper transport organization, and constructs a fault tree with 37 indirect events and 60 basic events. The FTA method was verified using TopEvent FTA software [15], confirming the accuracy of the analysis and providing a foundation for future studies that could incorporate specific risks, detailed probabilities, and tailored threat assessments for different hazardous goods.

The bow-tie analysis [12] combines FTA and ETA to analyse a critical event by identifying its causes and consequences, defining preventive controls on the left side and mitigation controls on the right side, and offering a comprehensive approach to risk management. Taubert et al. [16] utilized the Bow-Tie method for operational risk assessment in Genoa Port's hazardous goods container terminal, focusing on identifying potential hazards, their causes, and consequences. By combining FTA to trace the causes and ETA to evaluate potential consequences, the Bow-Tie method helped visualize and analyse accident scenarios, such as flash fires, explosions, and toxic releases, to assess their frequency and severity. The findings contributed to the development of risk mitigation strategies and the optimization of terminal design for enhanced safety and environmental protection.

The consequence/probability matrix is a flexible tool used to analyse and rank risks by evaluating the likelihood and severity of consequences, helping prioritize serious risks for treatment [12]. Gheorghe et al. [17] developed a comprehensive risk assessment model for rail TDG that combines a consequence matrix with FTA/ETA to determine the likelihood and impact of loss of containment (LOC) events. They use a Master Logical Diagram (MLD) to map out potential causes of LOC and assess risk based on the specifics of infrastructure and the surrounding environment. The findings are presented through a Complementary Cumulative Distribution Function (CCDF) and supported by GIS-based visual maps, allowing for targeted decision-making and focus on high-risk zones. Madej and Pająk [18] conducted a consequence analysis to assess the societal risk for communities living or working within a six-kilometre radius of national roads in Poland, focusing on accidents involving explosive and toxic dangerous goods. This analysis used GIS-based population density data, considering daytime and nighttime conditions, to estimate the number of people at risk in different buildings along these roads. The results were presented as risk maps for various accident scenarios, providing valuable insights for operational planning and prioritizing safety measures.

Fuzzy logic methods and Bayesian networks are increasingly applied in risk analysis [19, 20] to address uncertainty and complex interdependencies among risk factors. Fuzzy logic enables the incorporation of qualitative, imprecise, or vague data by representing risk variables through linguistic terms, such as "low" or "high," rather than requiring precise numerical values. On the other hand, Bayesian networks provide a probabilistic framework for modelling the relationships between different risk factors, allowing for the calculation of the conditional probabilities of various outcomes. This approach is valuable in situations where risk factors are interconnected and influence each other, facilitating a more comprehensive understanding of potential risks and aiding in decision-making processes. Yang et al. [21] assessed the risks of sudden water pollution caused by hazardous materials transportation over tributary bridges, focusing on Baiyangdian Lake in North China. Using fuzzy language methods and Bayesian networks, the research identified key risk factors, including driver fatigue, vehicle deterioration, and adverse weather, and recommended preventive measures to mitigate the risk of water pollution incidents.

The purpose of the study is to provide an analysis of the TDG in Hungary, offering statistical insights into the volumes and types of hazardous materials being transported, such as flammable liquids and gases. It also includes a case study on the transport of bitumen, comparing the old and new FMEA methods. The case study evaluates risks in the bitumen transport process, identifying critical issues like seatbelt use, speeding, and inspection deficiencies. The comparison highlights improvements in risk identification and mitigation strategies, aiming to enhance the safety and efficiency of dangerous goods transport in Hungary.

2 TDG in Hungary – Statistics

TDG refers to the movement of materials or substances that pose risks to public safety, health, property, or the environment due to their hazardous nature. Various regulations and standards are enforced globally to ensure their safe handling and transportation. The types of transport for dangerous goods include road, rail, air, sea, inland waterways, and pipelines.

The statistical data on the TDG in Hungary from 2014 to 2023 illustrates trends in both national and international transport across various categories of hazardous materials [22]. Dangerous goods transport involves regulated handling of materials that pose risks to public safety or the environment. According to Figure 2, while the overall transport of such goods has seen a slight increase, national transport specifically has shown modest growth, even as international transport decreased. This trend may indicate a shift in the demand and distribution of dangerous goods within Hungary's domestic market, potentially influenced by factors like industrial activity or regulatory changes affecting cross-border transportation.

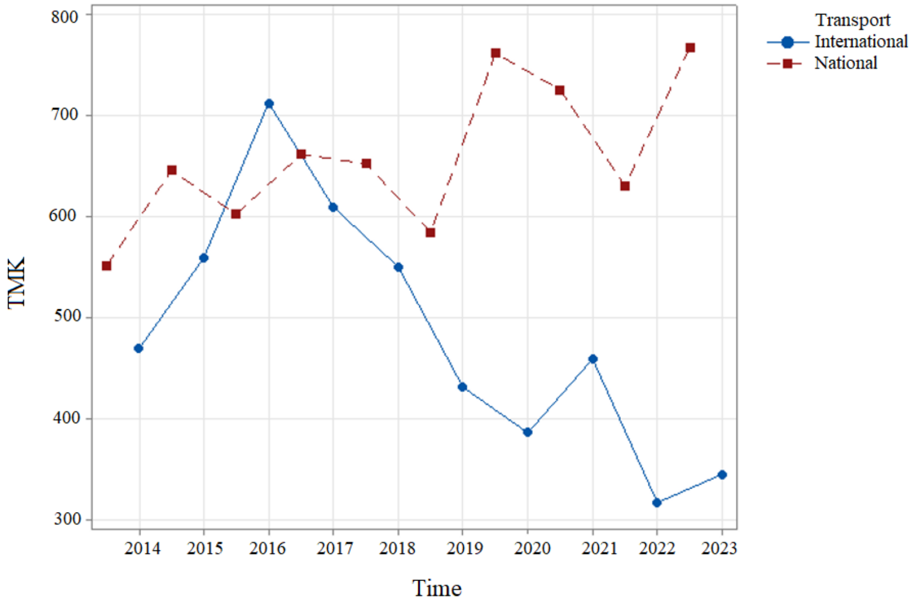

Figure 2. Transport of total amount of dangerous goods in Hungary between 2014 – 2023 in Million-Tonne Kilometre divided by the type of transport [22]

Table 1 breaks down the average yearly transport volume (in million tonne-kilometers or TKM) by categories of dangerous goods, highlighting flammable liquids [23] as the most transported category at 314.2 TKM. This is followed by miscellaneous dangerous substances (90.9 TKM) and gases (62.5 TKM). These figures suggest that Hungary's industrial sectors that rely heavily on flammable and gaseous materials, such as chemical manufacturing or fuel-related industries, may be key drivers in the national TDG volume. In contrast, less commonly transported goods, like infectious substances (2.4 TKM) and radioactive materials (0 TKM), indicate limited transport needs or stringent regulatory restrictions around these more highly controlled categories.

Table 1. Key parameters of our model

Type of Dangerous Goods	**Mean / Year [TKM]**
1. Explosives	7.3
2. Gases, compressed, liquified, dissolved und. pressure	62.5
3. Flammable liquids	314.2
4.1. Flammable solids	16.3
4.2. Substances liable to spontaneous combustion	6.2
5.1. Oxidising substances	6.4
5.2. Organic peroxides	9.6
6.1. Toxic substances	29
6.2. Substances liable to cause infections	2.4
7. Radioactive material	0
8. Corrosives	41.7
9. Miscellaneous dangerous substances	90.9

Further visual breakdowns in Figure 3, Figure 4 and Figure 5 provide insights into how specific types of dangerous goods are transported, with each transport mode chosen based on safety considerations and logistical practicality. Flammable liquids, for instance, show steady transport activity across different modes, while corrosive substances, gases, and toxic substances have variable transport volumes, due to differing industrial demands or safety protocols. These patterns suggest that some goods, like flammable liquids, have consistent demand and well-established transport processes, whereas others may be more subject to seasonal or industry-specific fluctuations [24].

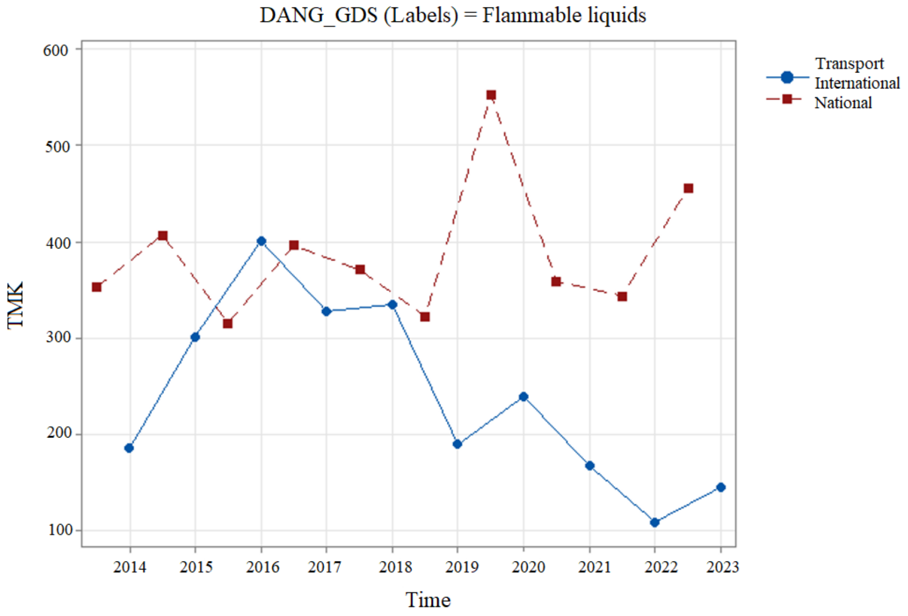

Figure 3. Transport of flammable liquids in Hungary between 2014 – 2023 in Million-Tonne Kilometre divided by the type of transport [22]

In summary, the data underscores Hungary's ongoing engagement in the national TDG, with a notable emphasis on flammable liquids and gases. The decrease in international transport might reflect localized production needs or adjustments in regional trade flows. Monitoring these trends is essential for aligning safety regulations with current transport demands and ensuring the secure movement of these hazardous materials across the country's transportation network.

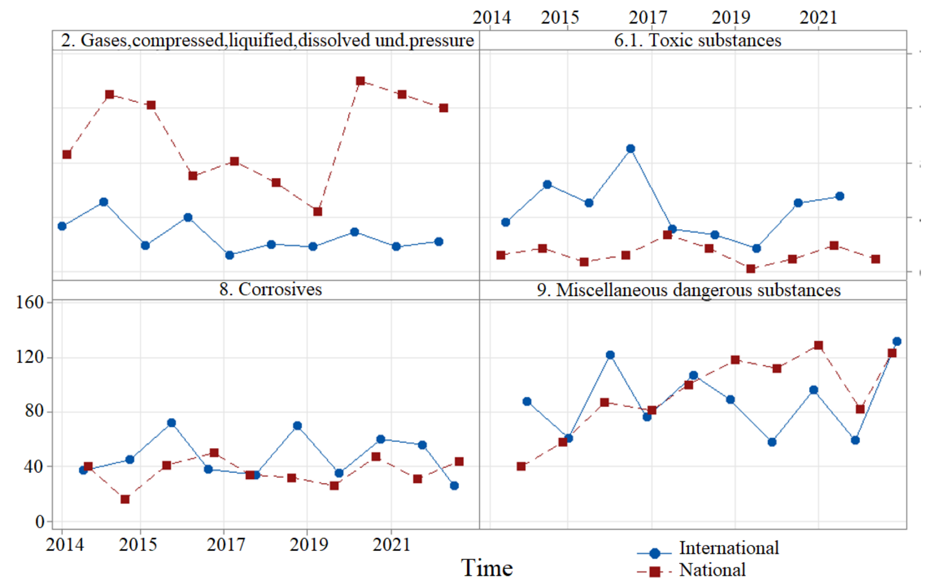

Figure 4. Transport of corrosive substances, gases, miscellaneous dangerous substances and articles and toxic substances in Hungary between 2014 – 2023 in Million-Tonne Kilometre divided by the type of transport [22]

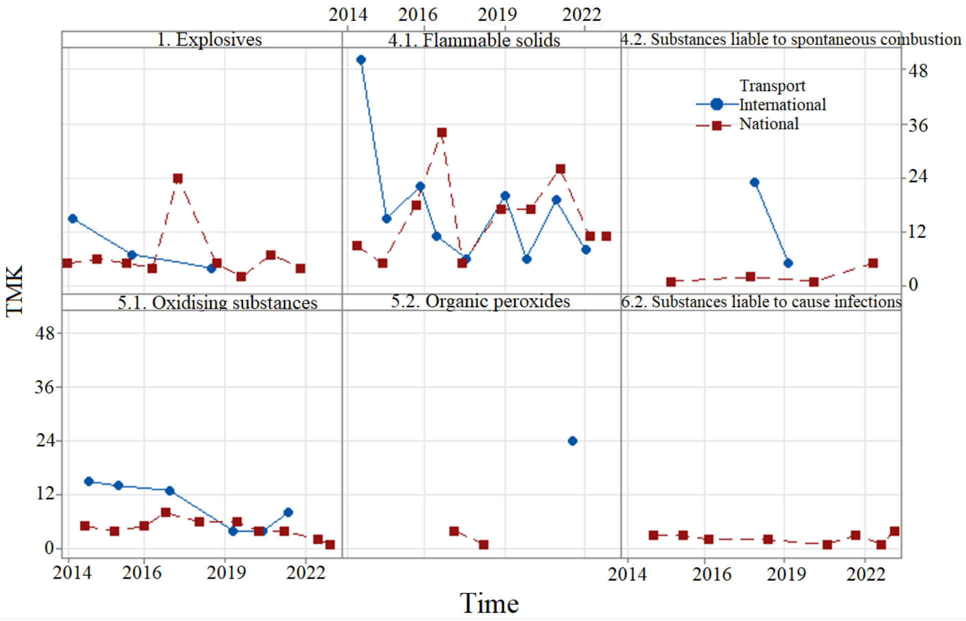

Figure 5. Transport of explosives, flammable solids, substances liable to spontaneous combustion, oxidising substances, organic peroxides and substances liable to cause infections in Hungary between 2014 – 2023 in Million-Tonne Kilometre [22]

3 Risk Management Process - A Case Study in Transporting Bitumen

3.1 About the Transport Process

The design of big semi-trailers for transporting bitumen is specialized (Figure 6). Bitumen may be carried using a tank body that complies with the tank code specified in the ADR. The semi-trailers are single-chambered, including corrugated plates internally to mitigate abrupt shifts of the material. The stainless-steel tank body, which transports bitumen at temperatures ranging from 170 to 200 degrees Celsius, is externally insulated with a thermal substance 10 to 15 cm thick, topped with a thin slate layer. The insulation prevents the substance from freezing.

The block diagram of the transport process is shown in Figure 7. The block diagram contains the main steps of the process. This block diagram is the input of the PFMEA method. Failure analysis aims to identify weaknesses and failure detects in the current bitumen transport process, eliminate risks, and establish a safer transport system.

Consequently, it is essential to identify corrective and preventive measures and monitor their impact.

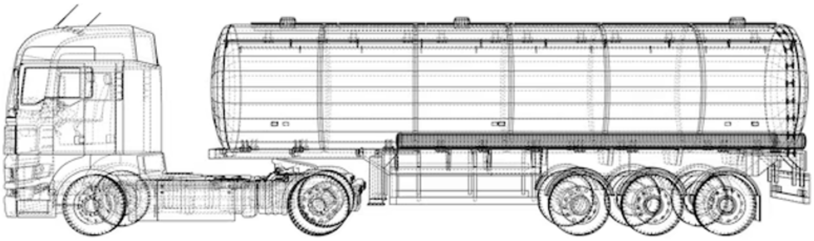

Figure 6. Semi-trailers for transporting bitumen

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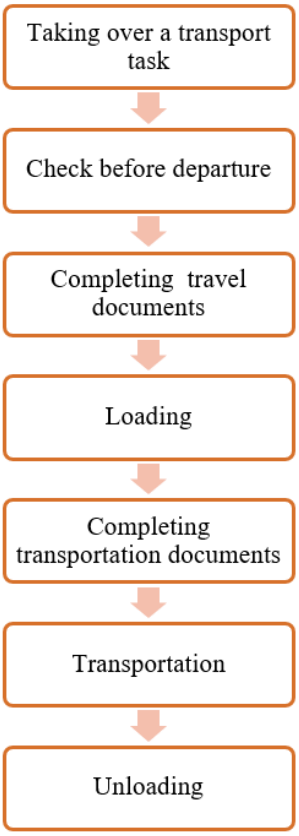


Figure 7. Bitumen transportation process

Note: This figure was prepared by the authors

3.2 Old PFMEA Method

In the PFMEA process, a team of specialists was tasked with identifying potential failures for every step of the chosen delivery process, analysing the risk of failure, and evaluating the risk based on the Risk Priority Number (RPN). The RPN was defined as follows:

$$RPN = \text{Severity}(S) \cdot \text{Occurrence}(O) \cdot \text{Detection}(D)$$

where,

Severity (S) - the severity (S) of the process's impacts on a scale from 1 to 10 points;

Occurrence (O) - rates the likelihood that the failure/failure cause will occur on a scale from 1 to 10 points;

Detection (D) - rates the likelihood that the problem will be detected on a scale from 1 to 10 points.

The highest score is assigned to the aspect of the process that fails to comply with safety or regulatory standards, leading to a deadly or extremely serious incident affecting both the driver and the environment. The team of experts gives 10 points for an extremely high frequency of failure reasons and 1 point for a rare frequency of failure causes. If the defect cannot be identified within the specified 10 points, the probability of the fault being 1 point is provided for definitive verification of the fault.

Table 2 illustrates the findings of the risk assessment according to the failure procedure and effect analysis. Three vital elements must be taken into consideration: transportation, pre-departure inspections, and acceptance of the transport assignment. A strategy must be formulated for minimizing the risk related to any or all of these key elements, as they are present in multiple critical chains. The most significant chains arise from inadequate control over process parts.

Table 2. Part of the FMEA analysis and RPN calculation

Critical Chains	RPN Value
Transport - No seat belt - Irresponsibility - No detect	410
Transport - Fast drive - Irresponsibility - No detect	374
Pre-departure inspection - Infringement - No inspection - No detect	334
Competition of transport document - Incorrect transport document - Lack of knowledge - No detect	304
Competition of transport document - Missing of transport document - Lack of knowledge - No detect	292
Pre-departure inspection - Incorrect inspection - Lack of knowledge - No detect	266

In considering the findings, the expert group has formulated three suggestions. The first relates to the development of the control group, the second to the installation of a camera in the vehicle, and the third to the identification of common faults in the completion of trip and transport documents. The expansion of the control group, along with preventive training and testing, would mitigate, but not eliminate, the risks and failures.

Drivers must be consistently checked to provide management with insights into their performance and conformity to standards. The enlargement of the control group is necessary. The new person will be accountable for routine inspections of the bitumen sector, including the behaviour of drivers, their interactions with customers, the correct completion of checklists, and the availability of documentation. A camera situated in the driver's cabin would record video for 0.5 to 1 minute every 5 minutes. The video content is supposed to be recorded on an SD card. The camera would so be capable of documenting penalties such as failure to use a seat belt, smoking, absence of protective clothes, ignoring rest periods, and transporting passengers. The submission of transportation forms is required by law. Inaccurate completion may lead to sanctions and postponement. It is advised that drivers complete regular refresher courses and assessments to address weaknesses in knowledge and reduce reckless and inattentive behaviour.

3.3 New PFMEA Method

The input of the new PFMEA method is the same block diagram of the process (Figure 8). The first task in conducting an FMEA is to carry out a structure analysis and a 4M analysis (Figure 9). In this case, the elements (Man, Machine, Material, Environment) that are related to each step in a relation are analysed.

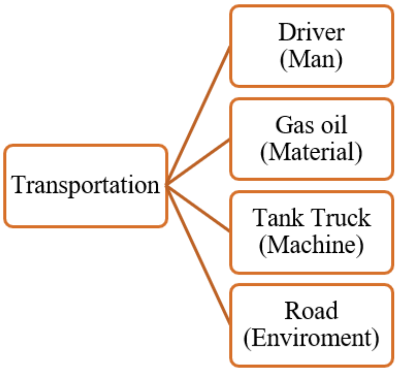


Figure 8. Analysis of selected process-step

Note: This figure was prepared by the authors

After defining the related elements, the functions are assigned to the process step and the related elements (Figure 9).

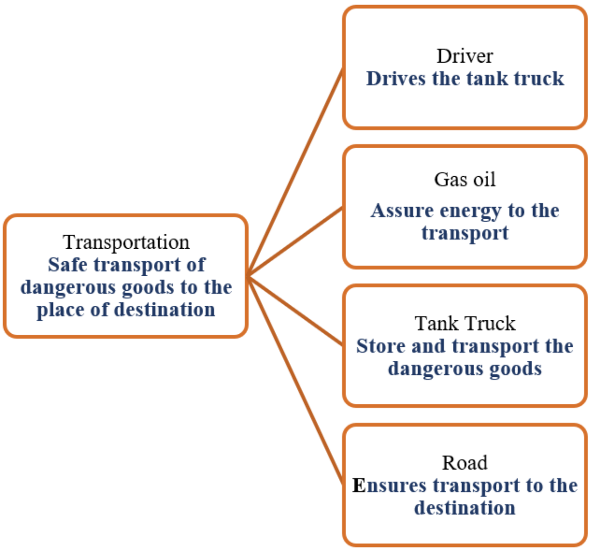


Figure 9. Function analysis of transportation (the functions with blue colour)

Note: This figure was prepared by the authors

After the function is analysed, the failure chain is listed. The focus element is the transport step. Figure 10 shows a failure chain. During transport, the function is corrupted, with the consequence that an accident occurs. The related element under investigation is the driver, below it is the function, followed by the potential causes that could have led to the accident. For the possible effects of an accident, we must consider not only the effect on the people involved in the accident but also the effect on the environment in case of damage to the transport vehicle.

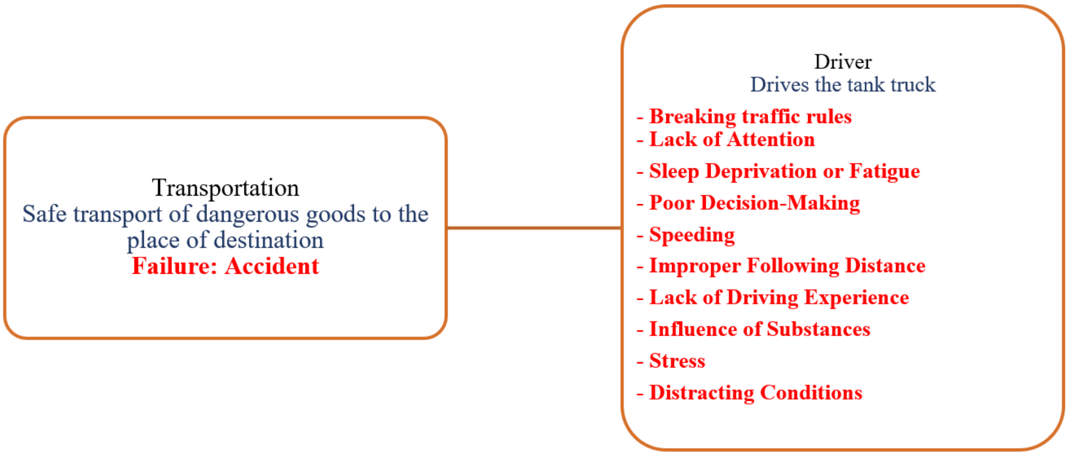


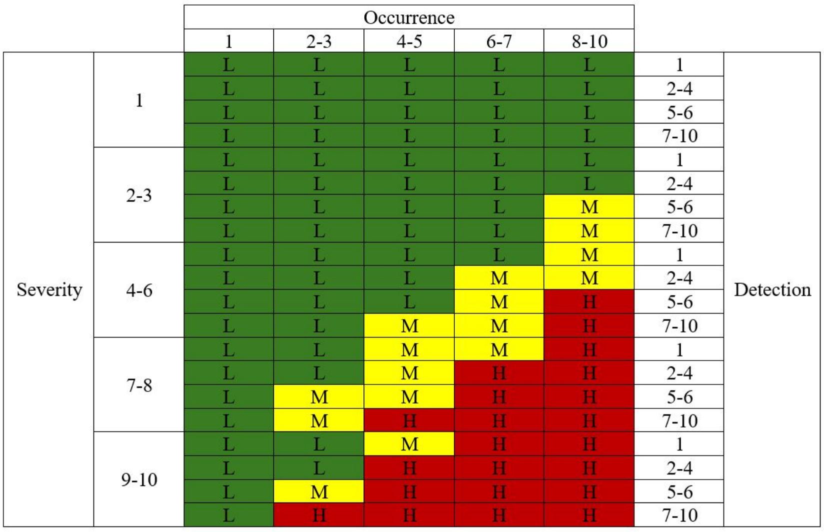
Figure 10. Failure chain and failure-causes - extract (the failure-causes in red)

Note: This figure was prepared by the authors

In terms of the consequences of the failure mode, one could be injury or death of the crash participants. If the tanker is damaged, there is a risk of fire and explosion, pollution of the environment, damage to health (people without protective equipment in the immediate vicinity), traffic disruption (during clean-up), and recovery and clean-up costs. As can be seen, the failure mode under consideration can have profound consequences.

Three aspects are considered when evaluating the failure. The first is the severity of the effect caused by the failure (S), followed by the frequency of failures (O) and the detectability of failures (D). For the last 2 factors, available statistics and the prevention and detection measures currently in place must be considered. For each of the three values, a scale of 1 to 10 points may be used. Due to the specific field, the meaning/content of the scale items may be different. This should be adapted to the process under consideration in each case.

After estimating the values, an AP (Action Priority) value is also defined, which refers to the priority of the action (Figure 11).



		Occurrence						
		1	2-3	4-5	6-7	8-10		
Severity	1	L	L	L	L	L	1	Detection
		L	L	L	L	L	2-4	
		L	L	L	L	L	5-6	
		L	L	L	L	L	7-10	
	2-3	L	L	L	L	L	1	
		L	L	L	L	L	2-4	
		L	L	L	L	M	5-6	
		L	L	L	L	M	7-10	
	4-6	L	L	L	L	M	1	
		L	L	L	M	M	2-4	
		L	L	L	M	H	5-6	
		L	L	M	M	H	7-10	
	7-8	L	L	M	M	H	1	
		L	L	M	H	H	2-4	
		L	M	M	H	H	5-6	
		L	M	H	H	H	7-10	
	9-10	L	L	M	H	H	1	
		L	L	H	H	H	2-4	
		L	M	H	H	H	5-6	
		L	H	H	H	H	7-10	

Figure 11. Action Priority [25]

If the priority is low, action can be taken. If it is medium, action should be taken. No action should be justified. If the AP value is high, then action should be taken, except in very justified cases. In this case, evidence should be provided to justify why the measures currently in place are proper for the risk identified.

The above example shows that the analysis is detailed, structured and flexible to the area. The risk assessment can be used throughout the risk management process.

4 Conclusions

TDG demands a rigorous approach to risk management to safeguard public health, environmental integrity, and regulatory compliance. This study has underscored the complexity of risks associated with hazardous materials and the necessity for systematic risk assessment methodologies such as FMEA, HAZOP, and environmental risk analysis. By methodically identifying, analysing, and evaluating potential hazards, organizations can effectively prioritize mitigation efforts, reducing the probability of incidents and ensuring safer transport operations. The presented case study on bitumen transport highlights how targeted risk assessment can illuminate critical vulnerabilities and prompt specific preventive measures, such as improved documentation practices, driver monitoring, and specialized vehicle features.

The findings show that successful risk management relies not only on identifying technical solutions but also on cultivating a proactive safety culture within the workforce. Enhancing training, expanding control and inspection processes, and implementing real-time monitoring systems can significantly reduce operational risks. Moving forward, the study recommends ongoing adaptation of risk management practices to address emerging challenges and technological advancements in transport safety. Future research could further refine these assessment tools and explore their integration with digital monitoring technologies, thereby advancing the safety and reliability of hazardous materials transport.

Funding

This work is funded by ERASMUS-EDU-2022-CBHE-STRAND-2 (Grant No.: 101082187).

Data Availability

The data supporting the research findings on road freight TDG, as provided by EUROSTAT, is officially available. This dataset includes detailed information on the TDG, broken down by type of goods and territorial coverage.

Acknowledgements

The authors would like to express their gratitude to the Transport of Dangerous Goods - Modernization of Curricula and Development of Trainings for Professionals in the Western Balkans HEIs / DGTRANS project for their support. This project, funded under ERASMUS-EDU-2022-CBHE-STRAND-2 (Project number: 101082187), has significantly contributed to the success of this research. We appreciate the opportunity to be part of this initiative and extend our thanks for their financial and logistical aid.

Conflicts of Interest

The authors declare no conflict of interest.

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