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Refining the safety design of rail tunnels in the EU using systems thinking

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Tunnels have developed from basic infrastructure into complex systems with many interconnected components. When designing a railway tunnel, other factors like human behavior and the technical systems of the trains add to this complexity. Traditional safety analysis methods often fall short in addressing this complexity, highlighting the need for a new approach to railway tunnel fire safety. This article sets out to investigate whether methods incorporating systems thinking into railway tunnel safety design could improve tunnel safety. A framework incorporating both STPA with more traditional engineering is used to analyze a prescriptive design as part of a case-study. Based on 'common' fire scenarios for railway systems, results show that a prescriptive design provides inadequate control in protecting tunnel users from heat and smoke. The article reveals that while the current regulatory framework at the EU level aims to incorporate systems thinking into the design process, several critical gaps hinder its practical implementation. The integration of safety assessment methods based on systems-thinking, combined with traditional risk analysis methods, holds significant potential for improving railway tunnel safety design. By combining methods like STPA with tools such as CFD, designers can better analyze complex socio-technical interactions and provide robust, cost-effective safety solutions.

Keywords: Tunnel fire safety, Railway tunnel, Systems safety, STPA.

1. Introduction

Over the past few decades, tunnels have evolved from basic infrastructure projects to intricate systems with highly interconnected components (PIARC 2011), also described as "safety-critical sociotechnical systems with high interactive complexity" (Tonk and Boussif 2024, 1). This evolution is driven by increasing tunnel lengths, the integration of advanced technical systems, and the introduction of digitalization and artificial intelligence. Additionally, human behavior during fire situations and the technical systems on trains add to this complexity. Traditional safety analysis methods, despite their wide acceptance and utility, often fall short in addressing this multifaceted complexity, highlighting the need for innovative approaches (Oginni et al. 2023).

Significant tunnel fires in the early 2000s increased concerns regarding tunnel user safety during fires (UNECE 2003), particularly in the EU, and spurred substantial research and regulatory reforms. Ingason, Li, and Lönnermark (2024) mention that the potential for mass casualty incidents is higher in railway tunnels compared to road tunnels. However, these event occur less frequent. Beard and Carvel (2012) and Ingason, Li, and Lönnermark (2024) identify 16 'significant' railway tunnel fires between 1980 and 2008, resulting in at least 646 fatalities and 566 injuries. In this same time span 47 'significant' road tunnel fires are identified, resulting in 199 fatalities and 446 injuries. Although these numbers carry some uncertainties, they underscore the high-consequence, low-frequency nature of railway tunnel fires.

The societal impact of tunnel fires can vary significantly between countries. While some countries experience only logistical disruptions, others face severe consequences. For mountainous countries like Norway, Italy, and Austria, railway tunnels play a critical role in ensuring connectivity and national security. Prolonged downtime for key tunnels can disrupt the transport of people and goods, hinder military logistics, and negatively affect communities reliant on these vital links. Adding societal value to the railway tunnel design adds another layer of complexity which needs to be accounted for.

Directive (EU) 2016/797 (2016) requires infrastructure open to the public to limit any human safety hazards, e.g. during fires. However, while reliability acceptance criteria are clearly defined for technical systems, such as frequencies below 10^{-7} or 10^{-9} operating hours (Regulation (EU) No 402/2013 2013), such clear acceptance criteria are mostly lacking regarding the safety of passengers and staff. Regulation (EU) No 1303/2014 (2014) provides largely prescriptive solutions for safety design of railway tunnels. Common safety targets for the system as a whole, and for subsystems where feasible, are expressed in terms of the following safety evaluation criteria: 1) the application of codes of practice, 2) a comparison with similar systems, or 3) an explicit risk estimation. When performing a risk assessment, prescriptive requirements will lead to an increased focus on the application of codes of practice. This practice, however, contradicts with the original intent of the regulatory framework requiring a systems approach.

The complexities discussed above underline the need for an updated approach to railway tunnel safety during fires. Chapter 3 will start by analyzing the current regulatory framework for railway tunnels safety design. Chapter 4 focuses on systems thinking, how this can improve railway safety design and present research comparing traditional risk analysis methods with those implementing systems thinking. These two chapters will provide a basis for the case study presented in chapter 5, which will test the feasibility of a chosen risk analysis method implementing systems thinking and analyze how the findings from this case study compare to the findings in previous chapters.

2. Method

This article addresses the evolving complexities in railway tunnel safety and the necessity for a new approach to enhance user safety during fires. This problem is approached with the following hypothesis:

The incorporation of systems thinking as a complementary approach in railway tunnel safety design can significantly improve the overall safety design of railway tunnels.

To evaluate this hypothesis, the following research activities were undertaken: 1) Identify and analyze European regulations for railway tunnel safety design, 2) Identify key issues related to safety in railway tunnels, 3) Map strengths and weaknesses of both current risk analysis methods used for railway tunnel safety design and those implementing a systems approach, 4) Analyze how the different tools can complement each other and provide a better decision-making basis when designing railway tunnels, and 5) Recommend solutions for improved practice.

Tonk and Boussif (2024) highlights that much of the research on systems-thinking methods, like STPA in railway systems, predominantly focuses on train collisions and derailments. This focus may stem from the clear acceptance criteria for technical systems outlined in railway regulations. However, no explicit performance-based acceptance criteria exist for passengers and staff safety during railway tunnel fires. To address this gap, this research specifically concentrates on improving the safety design of railway tunnels for its users during fires. By applying a systems-thinking approach and examining its integration with existing methods, this study aims to provide a framework for enhanced railway tunnel safety.

3. Current Framework for Railway Tunnel Safety Design

When investigating the effects of implementing methods incorporating systems thinking, it is important to start by understanding the current regulatory framework. This chapter examines key regulations and directives governing railway tunnel safety, emphasizing their scope, application and limitations in addressing the complexity of modern railway tunnels.

3.1. *Regulatory overview and hierarchy*

Regulation (EU) 2016/796 (2016) defines the responsibilities of the European Union Agency for Railways (ERA). Its primary objective is to facilitate a unified European railway area by ensuring high levels of safety and interoperability, while simultaneously enhancing the railway sector's competitiveness (Regulation (EU) 2016/796 2016, 8).

Directive (EU) 2016/797 (2016) divides the EU railway system into structural and functional subsystems, forming the foundation for the development of eleven Technical Specifications for Interoperability (TSIs). While several TSIs only cover one single subsystem, the TSI for safety in railway tunnels, Regulation (EU) No 1303/2014 (2014), covers several subsystems to collectively produce 'safety in railway tunnels' as an emergent property. Complementing this is Regulation (EU) No 402/2013 (2013), which provides a framework for risk evaluation and assessment.

Further analysis focuses on these two regulations: Regulation 1303/2014 (TSI SRT) and Regulation 402/2013, to assess their effectiveness in guiding railway tunnel safety design.

3.2. *Regulation 1303/2014*

The primary goal of TSI SRT is to achieve “an optimal level of safety in tunnels in the most cost-efficient way.” Its scope is focused on risks to passengers and staff, excluding broader considerations like societal needs for tunnel availability. Moreover, it explicitly delegates responsibilities for emergency personnel to national legislation and assumes that Fire and Rescue Service (FRS) personnel will prioritize saving lives over firefighting. Notably, the regulation acknowledges that some fires in railway tunnels may exceed the capacity of local emergency services, necessitating additional safety measures.

TSI SRT prohibits the application of codes of practice as risk acceptance for railway tunnels, ref. chapter 1, instead emphasizing the development of comprehensive emergency plans. These plans consider a wide range of evacuation scenarios, including the interaction between evacuation times and emergency personnel response times. While explicit risk estimation can provide critical insights into how specific fire scenarios impact evacuation, the regulation offers limited guidance on constructing effective evacuation scenarios, effectively relying heavily on designers and local authorities to self-regulate the safety of railway tunnels.

The regulation imposes various prescriptive safety requirements, such as distance between emergency exits and dimensions of emergency doors. While these requirements provide baseline safety measures, their rigidity may conflict with the flexible decision-making needed to address unique tunnel contexts. Moreover, the absence of detailed guidelines for evacuation scenario development creates uncertainty in aligning these prescriptive measures with actual safety outcomes.

3.3. *Regulation 402/2013*

Regulation 402/2013 outlines a general risk assessment framework for railway systems. It requires a clear definition of the systems’ objectives, its boundaries, and its physical and functional interfaces. The hazard identification process must focus both on the system under review, its functions and its interfaces.

The regulation adopts the CENELEC/EN 50126 V-cycle, which has many similarities to the traditional systems engineering V-model. This iterative process integrates hazard identification, risk evaluation, and mitigation, aligning with a broader systems-thinking approach.

Traditional risk analysis methods, such as Failure Mode and Effects Analysis (FMEA), Hazard and Operability Studies (HAZOP), and Fault Tree Analysis (FTA) are commonly applied under this framework (Oginni et al. 2023). While effective in technical risk analysis, these methods often struggle to incorporate socio-technical factors, such as human behavior and interactions with technical systems, which are critical in emergencies like railway tunnel fires.

4. Systems Thinking and Comparison with Traditional Risk Analysis Methods

4.1. *Defining systems thinking*

A system is broadly defined as an interrelated collection of elements that are arranged to accomplish a specific goal. Key components of a system include: 1) a clearly defined goal, 2) elements that together achieve this goal, and 3) connections or relationships between these elements. Systems are often hierarchical, with elements and sub-elements that can exist within larger systems. A system embodies a sense of wholeness, with mechanisms to maintain its integrity (Checkland 1999).

Arnold and Wade (2015, 675) defines systems thinking as: “Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system.”. Monat and Gannon (2015, 11) argue that systems thinking “is a perspective, a language, and a set of tools.”

Within systems thinking, safety is an emergent property achieved through appropriate control actions on the system. Accidents occur when safety constraints fail to be enforced during the development, design, or operation of the system (Leveson 2011).

4.2.*Systems thinking in EU railway regulations*

The EU regulatory framework emphasizes a systems approach, as highlighted in Directive (EU) 2016/798 (2016, 2): "This Directive applies to the rail system in the Member States, which may be broken down into subsystems for structural and functional areas. It covers safety requirements for the system as a whole, including the safe management of infrastructure and of traffic operation and the interaction between railway undertakings, infrastructure managers and other actors in the Union rail system."

While Directive (EU) 2016/798 advocates for a systems approach, gaps remain in its practical application, especially in the safety design of railway tunnels. For instance: 1) TSI SRT focuses heavily on prescriptive requirements, which limit flexibility in addressing emergent system behaviors, 2) Neither TSI SRT nor Regulation 402/2013 provide clear, functional acceptance criteria for tunnel user safety. One example of a performance-based criteria is the traditional ASET/RSET requirement used for buildings: *ensuring that the required safe egress time (RSET) significantly exceeds the available safe egress time (ASET) during a fire*.

4.3.*Systems-Theoretic Process Analysis (STPA)*

STPA, a hazard analysis method rooted in systems thinking, employs a top-down approach to identify potential hazards (Leveson 2011). Unlike traditional methods which are based on linear cause-and-effect chains or reductionism, STPA focuses on control and constraints within a system (Oginni et al. 2023; Leveson 2011). This makes it particularly effective for systems with complex interactions, such as those involving humans, software, and dynamic behaviors. STPA has been widely adopted in sectors like aerospace, healthcare, and nuclear facilities (Tonk and Boussif 2024). A more detailed description on STPA can be found in Leveson and Thomas (2018).

4.4.*Comparison with traditional risk analysis methods*

Traditional risk analysis methods, such as FMEA, HAZOP, and FTA, have long been used for hazard identification and risk mitigation. Comparative studies highlight the following advantages of STPA: 1) *End criteria and efficiency*: STPA has a clear endpoint, reducing analysis time and avoiding unnecessary complexity (Kölln, Klicker, and Schmidt 2019), 2) *Reduced dependence on expert knowledge*: STPA's structured approach reduces reliance on the analysts' knowledge and experience compared to HAZOP/HAZID (He et al. 2023; Joung et al. 2018), 3) *Early-stage applicability*: STPA can be applied during the early design stages, whereas traditional methods often require more detailed designs (Kölln, Klicker, and Schmidt 2019), 4) *Broader hazard coverage*: STPA excels in identifying hazards arising from interactions between system elements, software, and environmental factors, as well as producing more detailed scenarios (Bensaci et al. 2020; Benhamlaoui et al. 2020; Duan 2022; He et al. 2023; Joung et al. 2018).

However, STPA's purely qualitative nature may necessitate a combination with quantitative methods to enhance hazard coverage (Bensaci et al. 2020). Most studies suggest that integrating STPA with traditional methods yields the most comprehensive results (Kölln, Klicker, and Schmidt 2020; Benhamlaoui et al. 2020; Bensaci et al. 2020; Riemersma et al. 2020).

4.5.*Applications of STPA in railway safety*

Dunsford and Chatzimichailidou (2020) discuss how STPA could supplement the EU framework for railway safety. Oginni et al. (2023) conducted a case-study demonstrating STPA's application in a specific railway project. However, both these articles focused on technical systems and did not focus on the safety of tunnel users during fires.

Bjelland et al. (2015) proposed a framework combining systems theory, coherence theory, and resilience engineering. This framework integrates STPA with more traditional engineering practices, including scenario analysis. Its steps include: 1) System description, 2) Identification of functional requirements and safety constraints, 3) Scenario analysis, 4) Outline of safety barriers, and 5) Barrier performance and system analysis. While step 3 ensures a minimum level of safety, steps 4 and 5 address key uncertainties, aligning systems thinking with engineering best practices. Due to this combination, this framework is used in a partial case-study to exemplify how implementing systems thinking in the safety design of railway tunnels can improve user safety.

5. Case-study of Railway Tunnel Fire

This case-study evaluates a prescriptive railway tunnel design using the framework proposed by Bjelland et al. (2015). The purpose is not to present a comprehensive analysis but to illustrate how the framework can be applied in a railway tunnel context. The focus is on identifying issues within a prescriptive design that require further investigation and refinement.

5.1.Step 1: System description

The primary problem statement is: *How to design a railway tunnel which can provide a sufficient level of safety for its users (passengers and train staff) during a fire?*

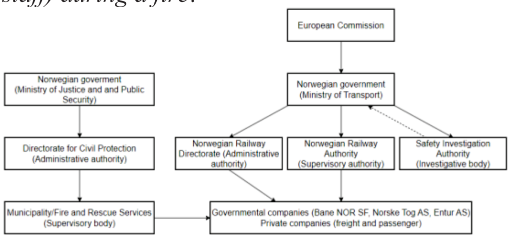

Figure 1: The socio-technical hierarchy

A socio-technical hierarchy (Figure 1) and context diagram (Figure 2) were developed to identify stakeholders and environmental factors influencing the system. A stakeholder analysis produced the following functional requirements related to the safety of tunnel users and FRS: 1) Protect tunnel users from fire hazards as the result of the tunnel's designed and maintained level of emergency preparedness, and 2) Protect FRS personnel from untenable conditions during rescue operations inside the tunnel, as the result of the tunnel's designed and maintained level of emergency preparedness.

5.2.Step 2: Identification of functional requirements and safety constraints

Building on the stakeholder analysis, potential system losses were identified (Table 1). Based on the definition of a hazard in Leveson (2011); Leveson and Thomas (2018), the system-level hazard is identified as 'Fire in tunnel'. This is further detailed in Table 2.

Table 1: Identification of losses

ID	Description
L1	Loss of life or serious injury
L2	Loss of or damage to train
L3	Loss of mission, significant delays or performance issues
L4	Loss of customer satisfaction, negative impact on reputation
L5	Loss of or damage to tunnel structure
L6	Loss of or damage to tunnel equipment

Table 2: Identification of system-level hazards

ID	System-level hazard	Ass. losses
H1.1	Fire in tunnel equipment.	L1, L2, L3, L4, L5, L6
H1.2	Fire on train.	L1, L2, L3, L4, L5, L6

The balance between the available safe egress time (ASET) and the required safe egress time (RSET) is crucial for tunnel user safety during a fire. Tunnel users should reach a place of safety before the available safe egress time runs out, meaning ASET≥RSET. During the design phase, a certain safety margin should be added to account for any uncertainties and add resilience. This is where the importance of the factor 'time' comes into play.

ASET is influenced by fire development, fire size, and heat/smoke movement. RSET is influenced by detection, warning of tunnel users, guidance, and evacuation provisions. Figure 3 illustrates a preliminary control structure addressing these factors. Based on the hazards, system-level constraints were identified in Table 3.

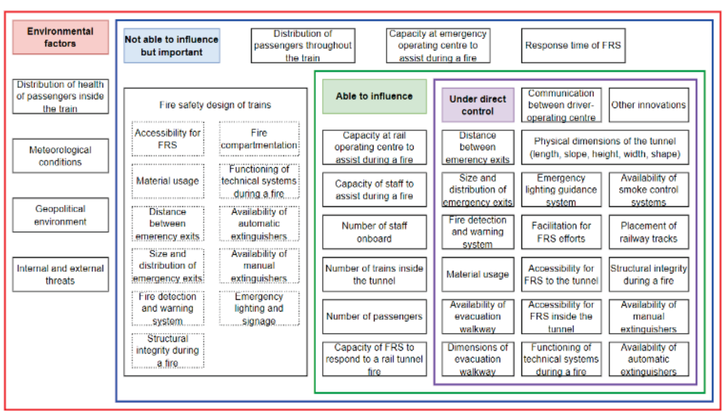

Figure 2: Detailed context diagram

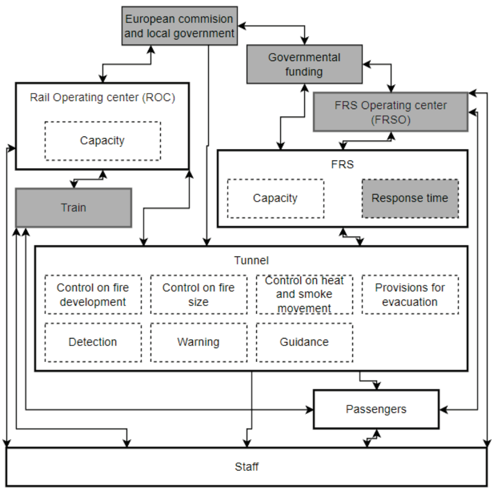

Figure 3: Preliminary control structure

Table 3: Identification of system-level constraints

ID	System-level constraint	Hazards
SC1	Prevent fires from occurring.	H1.1, H1.2
SC2	Tunnel must provide a sufficient safety margin between ASET and RSET, to support safe egress of tunnel users during a fire.	H1.1, H1.2
SC3	Tunnel must support FRS in their efforts to rescue those in need during a tunnel fire	H1.1, H1.2

5.3. Step 3: Scenario analysis

For this part of the analysis a tunnel is used, for which its cross-section is shown in Figure 5. The tunnel is 5,000 meters long with a 1.5% slope, designed to meet all prescriptive requirements from TSI LOC&PAS and TSI SRT.

The following 'worst-case' scenario is identified: "Fire on a train unable to exit the tunnel, stopping 100 meters past the nearest emergency exit. The fire begins at the rear of the train, spreading to all carriages, requiring tunnel users to evacuate 900 meters uphill to the next exit.". For this scenario a design fire was made using Ingason, Li, and Lönnermark (2024), assuming a steel frame train made up of 4 carriages. The design fire is shown in Figure 4.

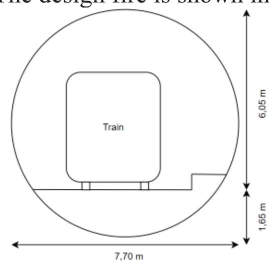

Figure 5: Cross-section of tunnel

Acceptance criteria and hand calculations for the ASET-analysis were based on Ingason, Li, and Lönnermark (2024). For the RSET-analysis, each carriage (3mx19,5m) was filled with 195 people connected to a 900 m walkway. Results of the ASET and RSET analysis are shown in Figure 6. The analysis showed that the chosen prescriptive design and assumptions failed to adequately control heat and smoke movement. RSET exceeded ASET for nearly all acceptance criteria near the fire, while visibility was unacceptable throughout the evacuation path. This highlights insufficient control loops in the design, necessitating further hazard identification, revised constraints, and additional safety measures.

5.4. Step 4 and 5: Further analysis

Steps 4 and 5 are not performed as part of the case-study but would focus on assessing key uncertainties and identifying additional safety measures once an acceptable design was produced in step 3. Component failures, interactions between system elements, and remaining risks would be analyzed to determine if

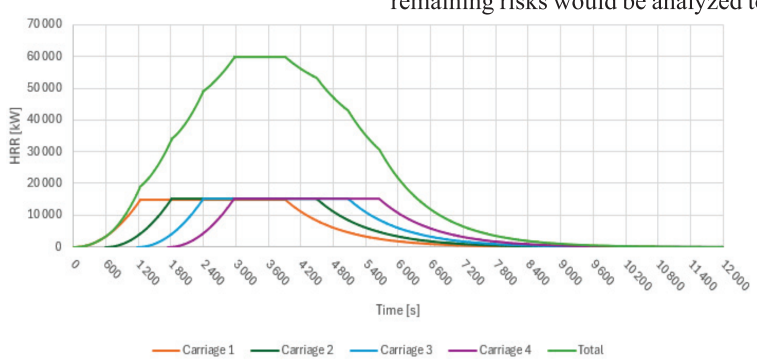

Figure 4: Design fire

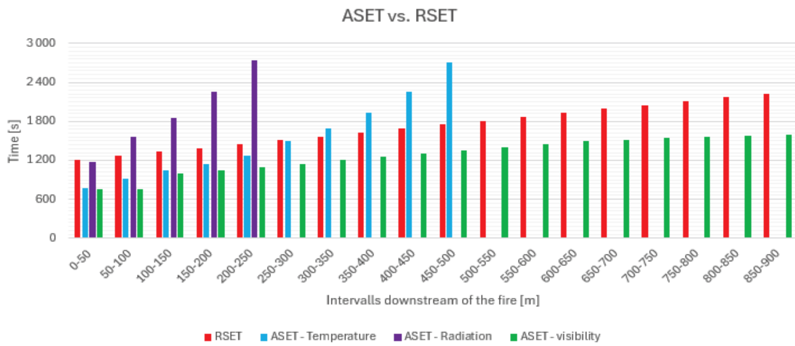

Figure 6: Results of ASET vs. RSET-analysis

the design complies with functional requirements and if additional measures are required.

6. Discussion

This article examines the integration of systems thinking into railway tunnel safety design, particularly during fires, by comparing current risk assessment methods with systems-based approaches. Results reveal significant gaps in existing frameworks, challenges in regulatory applications, and the potential for STPA to enhance railway tunnel safety design.

Firstly, TSI SRT claims to focus on the risks to passengers and staff. However, it lacks clear safety goals during a fire to protect passengers and staff. Additionally, it has several prescriptive safety requirements, providing a baseline for safety levels. However, it prohibits the use of a comparative approach to document the safety of railway tunnel users. Instead, it puts a lot of faith in the development of good emergency plans, while offering limited guidance and leaving significant discretion to designers and local authorities.

These findings show some fundamental limitations to improving railway tunnel user safety. Such rigidity limits the possibility to achieve its initial goal to provide “an optimal level of safety in tunnels in the most cost-efficient way”. This way of thinking points towards the idea that standardization and prescriptive solutions are preferred, ignoring the complexity of railway tunnels across the EU. Although this way of approaching safety is the easier regulatory direction, it ignores local contexts for each individual tunnel. One tunnel might be situated in a rural area, with only part-time FRS, long response time and little funding. Another might be placed in a densely populated area with a highly funded FRS and short response times. These tunnels have vastly different safety levels, and ignoring these environmental factors can create great differences in safety levels between tunnels across the EU.

The previous example not only shows that environmental factors can contribute to great differences in safety levels between tunnels, but it also provides a good example of how a systems approach can complement traditional risk analysis methods used today. As mentioned in chapter 4.4, the purely qualitative nature of STPA necessitates the use of quantitative methods to document the reliability of technical systems. Additionally, studies have shown that this combination provides broader hazard coverage.

The case-study attempts to start a discussion on implementing systems thinking into the design of railway tunnels by using the presented framework. It increases the focus on designing the safety system of railway tunnels through a set of design scenarios and increased understanding of local limitations and possibilities. The case study findings directly challenge current regulations and methods by demonstrating that a prescriptive tunnel design failed to control heat and smoke movement, leading to unsafe evacuation conditions. While traditional methods are well-established in todays’ safety framework, the findings suggest they are insufficient for complex systems with sociotechnical features—reinforcing the need for a broader systems approach. To combat these identified insufficiencies, a complementary approach is proposed to take advantage of the strengths and weaknesses of each method.

7. Conclusion

This article underscores the necessity of integrating systems thinking into railway tunnel safety design, particularly in fire safety scenarios.

The findings support the hypothesis that a systems approach can complement and improve traditional railway tunnel risk assessments by addressing emergent behaviors, sociotechnical factors, and regulatory inconsistencies.

To improve railway tunnel safety, the study recommends: 1) Enhancing regulatory frameworks by developing clear performance-based safety criteria, 2) Incorporating sociotechnical factors by strengthening the integration of fire and evacuation modeling into tunnel evacuation planning, 3) Incorporating systems thinking in risk assessments.

By integrating systems thinking and performance-based safety assessments, railway tunnel designs can achieve greater resilience and safety for tunnel users. This approach aligns with evolving regulatory expectations and technological advancements in railway safety.

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