Managing Disaster Risks in Underground Transportation Infrastructure - A Comprehensive Analysis of Safety Targets and Practices

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ABSTRACT

This study examines the management of disaster risks in underground transportation infrastructure, focusing on the safety challenges posed by large-scale accidents. By reviewing international guidelines and evaluating Swedish projects, the research identifies risk criteria, such as FN- curves and the ALARP principle, used to assess societal risks across sectors like nuclear power and dam safety. The findings reveal gaps in Swedish regulations regarding disaster risk management, especially for complex environments such as the space surrounding platform area in underground stations. Recommendations are provided to strengthen Swedish regulations and standards by incorporating international best practices and enhancing risk-informed decision-making. This work aims to contribute to safer, more resilient transportation systems and supports sustainable urban development by addressing the specific challenges of large-scale accident prevention in underground infrastructure.

KEYWORDS: Disaster, catastrophic risk, underground transportation infrastructure, safety criteria, FN-curves, ALARP principle, societal risk assessment, risk-informed decision-making, sustainable urban development.

Introduction

Context and relevance

This paper forms part of the research project Safety Objectives for Underground Stations [1], initiated by the Swedish Transport Agency and the Swedish Transport Administration. The project aimed at developing a unified model for defining and verifying minimum acceptable safety levels for platform enclosures, based on risk and socio-economic analysis. This paper presents a segment of this work, an analysis of disaster risk, contributing to the project's overarching goal of improving safety and efficiency in regulatory development.

In the event of a major accident in a location where large groups of people are present, there is potential for mass casualties under catastrophic circumstances. Society generally views accidents with multiple fatalities as unacceptable, yet this perspective often emerges only after an incident has occurred. The development of safety regulations is often accident driven. Beforehand, it is challenging to assess whether a risk is acceptable, particularly in preventive work for both minor and major accidents. Explicit guidelines are frequently lacking to support such assessments across sectors. Fortunately, no such accidents resulting in a very high number of casualties have yet occurred in modern underground infrastructure. However, this does not mean that it is appropriate to refrain from regulating this type of risk, thereby effectively leaving it to chance. While incidents involving multiple individuals have taken place, they have so far been of a smaller magnitude than the catastrophic scenarios considered in this context. Such an approach is not consistent with sustainable development and sound disaster risk management [2].

For certain environments, such as underground platform enclosure in mass transport systems, the risk of severe consequences exists, especially in complex evacuation scenarios involving large numbers of people and/or concurrent transport of hazardous materials. This raises questions about the need for special regulatory requirements to address such risks, potentially influencing infrastructure design and operation to mitigate unacceptable risks. Eliminating these risks entirely could restrict current or future transportation system capacity, necessitating a careful balance in decision-making and a thoughtful assessment of which stakeholders are best suited to make these determinations. Should decisions on such risks be made within individual projects, or should national guidance be established to standardize decision-making?

Although the primary focus of this study is Swedish risk regulation, its findings have broader relevance for countries facing similar challenges in managing disaster risks in underground transport infrastructure. Several international safety standards, such as those in nuclear and dam safety, demonstrate how systematic approaches to disaster risk management can enhance regulatory frameworks. Lessons learned from Sweden's approach may therefore be applicable to other nations developing safety targets for transportation infrastructure. Existing EU directives, such as those for tunnel safety [3], further highlight the role of national regulatory refinement, complementing the broader international perspective discussed above.

Purpose and objectives

The purpose of this paper is to enhance understanding of requirements for managing — through analysis, assessment, and control — accidents with significant consequences. The goal is to outline how the risk of severe accidents is addressed in various regulations. In addition to reviewing the scientific literature and regulations, the study examines two Swedish infrastructure projects, Sundbyberg Station and Centralstaden in Stockholm, to illustrate how risk assessment and disaster risk management are applied in practice. Based on these analyses, the study also provides recommendations for improving risk governance in the Swedish transport sector, particularly in underground infrastructure projects.

This study adopts an empirical approach by systematically analyzing how disaster risks are regulated across multiple sectors and jurisdictions. The research seeks to identify patterns, gaps, and regulatory principles that influence risk acceptance criteria. By examining documented safety regulations, risk criteria, and decision-making processes, the study contributes to the broader field of applied risk research. The methodology aligns with comparative policy studies, where regulatory frameworks are empirically assessed to provide insights into risk governance. This approach is commonly applied in disciplines such as disaster risk management, regulatory science, and safety engineering. While the work does not fit strictly within experimental research paradigms, it provides an empirical foundation for understanding how safety targets evolve and function in practice.

Background

Safety regulations have evolved from strictly risk-based comparisons to risk-informed frameworks that integrate quantitative criteria (e.g., FN-curves) with qualitative assessments. This shift, seen in nuclear power and dam safety, ensures a broader evaluation of risk beyond numerical thresholds. In some situations, additional factors must be considered to determine whether safety requirements are met. This is particularly relevant when evaluating if a safety goal has been achieved. Consequently, for certain assessments, criteria comparisons may need to be supplemented with other considerations, thus broadening the basis for evaluation. At the same time, risk level estimation remains an important component, requiring support to determine what constitutes high or low risk. Therefore, the question of how criteria are appropriately formulated cannot be disregarded. This approach has been primarily driven by the energy production sector, notably nuclear power and hydroelectric dams, where decision-making support in risk analysis has increasingly included information on uncertainty, cost-benefit analyses, risk reduction, and the impacts of different risk-reducing measures. Additionally, restrictions and limitations for facilities and infrastructure systems should also be part of such analyses.

An earlier project report summarizing the first part of the Safety Targets for Platform enclosure project [2] noted that risk acceptance criteria (RAC) are commonly used across several industries to aid decision-making. Many industries establish clear boundaries for acceptance criteria as the number of people exposed to risk increases, and separate evaluations are often needed for accidents with very large-scale consequences. While catastrophic incidents involving over 1,000 fatalities are a common benchmark for additional scrutiny, smaller-scale incidents can also have severe societal impacts. This paper focuses on risks with "catastrophic potential" or "disaster risk," for which standardized definitions and thresholds are often lacking. Nonetheless, many sectors employ quantitative criteria to guide decisions when managing risks of significant societal impact.

Systematic risk analyses, such as those utilizing FN-curves, are critical for assessing societal risks, but they inherently involve epistemic and aleatory uncertainties, which influence the reliability of probability and consequence estimates. This study highlights that risk assessment is not simply a mechanical comparison of probabilities and consequences; it also requires qualitative judgments about knowledge strength and the ability to predict rare, high-impact events. Addressing uncertainties, such as evaluating data quality and assumptions, plays a crucial role in risk-informed decision-making. While such uncertainties cannot be eliminated, they should not serve as a justification to neglect studying or managing these risks. Instead, systematic approaches provide a robust framework for navigating incomplete knowledge and ensuring decisions are informed by both quantitative data and qualitative insight.

Method

To understand and analyze how disaster risks are managed across various sectors and countries, a three-step approach was undertaken. The aim of this method was both to identify international applications of risk management and to examine how Swedish infrastructure projects address these risks in practice. A summary of the approach is provided below.

- Literature Review: A review of international and sector-specific guidelines and criteria was conducted to explore how quantitative risk criteria are applied across various sectors relevant to disaster risks. The study initially took a broad approach, aiming to identify diverse methods and principles used for managing large-scale risks. As the review progressed, it became evident that FN-curves and the ALARP principle are among the most commonly employed measures in sectors such as nuclear power, dam safety, and transport infrastructure where explicit risk governance was conducted. These tools were therefore given particular attention in the analysis due to their prominence and applicability in disaster risk management.
- Case Studies of Swedish Infrastructure Projects: Two Swedish infrastructure projects, Sundbyberg Station and Centralstaden in Stockholm, were analyzed to highlight how risk assessment and disaster risk management are applied in practice. These projects were selected based on their complexity and potential impact on large groups of people in underground environments.
- Analysis and Comparison: Identified criteria and methods from the literature review and case studies were compared to highlight similarities and differences between international and Swedish approaches to managing major accidents. The findings are used to suggest improvements to Swedish regulations and guidelines in the transport sector.

1. REGULATION OF DISASTER RISKS

Regulations addressing disaster risks are often reactive and based on past events. This approach poses challenges, given the limited empirical data on very large-scale accidents, primarily due to their low probability. Therefore, while empirical experience remains valuable, it must be supplemented with proactive strategies. Without such approaches, new risks could emerge without adequate mitigation, potentially for extended periods. In urban development, this could lead to long-term limitations in addressing these risks, embedding vulnerabilities that later become difficult to rectify.

In several industries, the need to explicitly account for disaster risks and to adopt protective measures that reduce both the likelihood and consequences of such events has grown significantly over the last

30 years. While some sectors have had these requirements for a long time, the 2011 Fukushima nuclear disaster highlighted the importance of this issue, accelerating both research and implementation of protective measures in areas where accidents with extensive consequences are possible.

In international agreements, such as the Sendai Framework [2], countries have committed to avoiding activities that introduce disaster risks into society as part of sustainable development goals. In Sweden, the responsibility for implementing this framework rests with MSB (the Swedish Civil Contingencies Agency); however, so far, implementation has not resulted in pronounced requirements that clearly influence how disaster risks are managed across different sectors or in planning and design. Notably, the Sendai Framework emphasizes the importance of proactive measures to reduce vulnerabilities and prevent new risks. Yet, despite these commitments, reports indicate that there has been limited progress in translating these principles into actionable, sector-specific guidelines or robust risk governance strategies [5].

Across sectors, there has been a growing emphasis on the need for specific requirements addressing disaster risk management. This is a recent trend, and various terms in international literature, such as Design Extension Condition, Beyond Design Accidents, and Severe Accident Management, are used to highlight this need. These terms refer to accidents with the potential for extensive injuries and fatalities, events that present significantly greater consequences than traditionally managed risks. This paper refers to such accidents as “disaster risks,” a term that, while potentially subject to future refinement, aligns with international terminology.

The regulation of disaster risks typically includes requirements across multiple aspects of an organization’s safety management system, from technical standards to training and emergency response, as well as facility location, management, and governance. Hence, it is not limited to be covered by only expressing a quantitative criteria on an acceptable risk level due to such accidents. Across all studied sectors, requirements related to “disaster” are integrated within the broader safety management framework rather than as isolated additions to traditional accident regulations. However, distinct requirements can be identified that specifically address large-scale accidents and disaster potential as one important component in such a safety management system.

Within organizations, requirements for disaster risk management are divided into various categories (comparable to high-level safety goals), including requirements for risk analysis, specific safety measures, and emergency management. For instance, in the nuclear industry, specific “design requirements” are established:

“A set of design extension conditions shall be derived on the basis of engineering judgement, deterministic assessments, and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant’s capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures. These design extension conditions shall be used to identify the additional accident scenarios to be addressed in the design and to plan practicable provisions for the prevention of such accidents or mitigation of their consequences” [4].

The requirement above clarifies, at a relatively high level within regulatory hierarchies, that very large accidents, those exceeding the design basis of the facility, need to be considered during facility design. Additionally, such analyses should influence both the preventive and mitigative safety measures. This requirement sits high within the requirements and objectives hierarchy and is subsequently broken down into more detailed requirements and quantitative criteria. In parallel, an emergency management requirement is set at the same hierarchical level, emphasizing the need for handling (analysis, assessment, decision-making, and implementation of measures) very large accidents within this domain.

Examples of Quantitative Criteria from Different Countries and Sectors

A literature review was conducted to identify countries and sectors where quantitative criteria are incorporated into managing large-scale accident risks. The figures below present several such criteria. It is evident that in countries and sectors where specific requirements exist for assessing the acceptability of disaster risks—particularly for incidents that could result in over 1,000 fatalities (intense scrutiny)—this determination is generally part of a formal approval process carried out by an external regulatory authority rather than by the developer alone. Thus, it is not solely the responsibility of the developer to decide, after conducting an assessment, whether the disaster risk has been sufficiently managed, even though the developer is ultimately accountable for the facility's safety during operation, including potential accident scenarios.

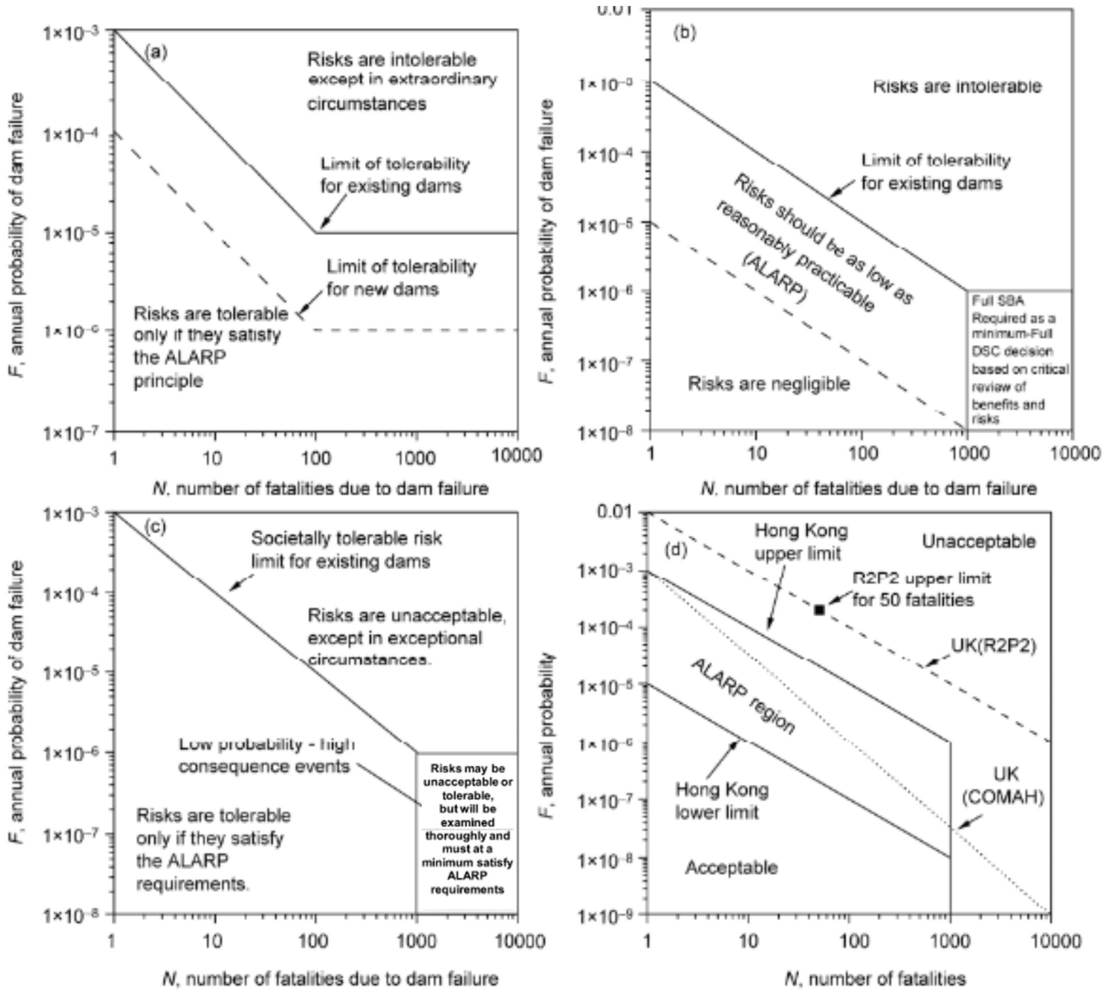


Figure 9. Examples of International Risk Criteria in the Power Plant and Dam Safety Sectors (a) ANCOLD [7], b NSW [8], (c) USACE [9] och (d) UK and Hong Kong [10] [11].

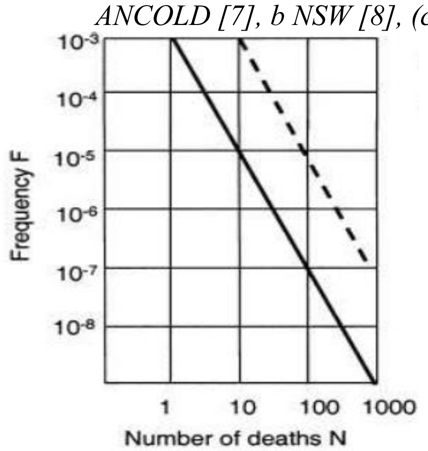


Figure 10. Country: Netherlands, Sector: Industrial Activities (solid line) and Transport (dashed line) [12].

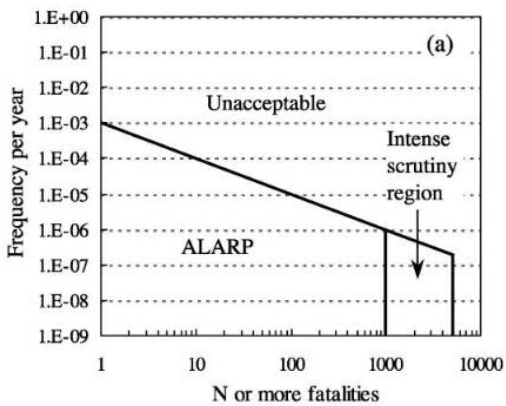
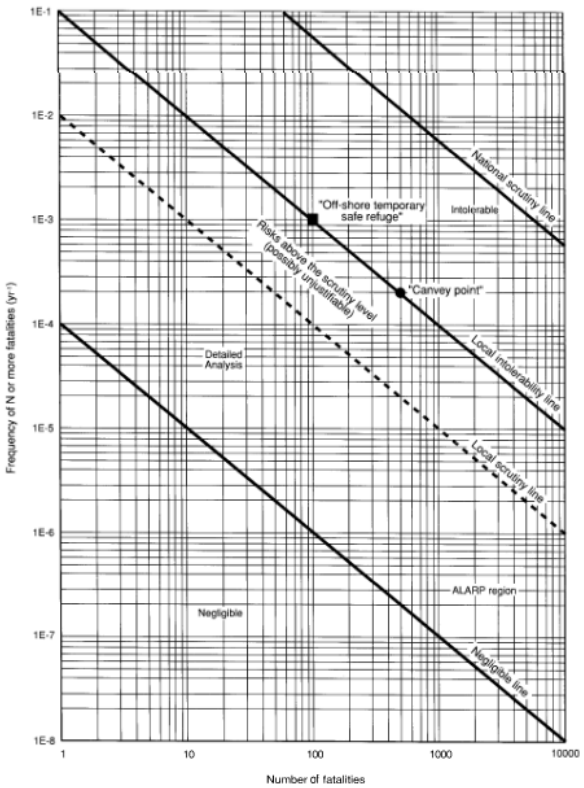


Figure 11. Country: Hong Kong, Sector: Landslides [13].



In Sweden, the so-called DNV criteria [12] have long served as standard practice in land-use planning, such as for developments adjacent to hazardous facilities or dangerous goods transport routes. No upper threshold for fatalities is included in the societal risk criteria. Instead, it is recommended that such issues be addressed qualitatively. Consequently, extrapolation to the right in Figure 13 is not advised, even if the dotted lines in the figure suggest it. The DNV report does not further elaborate on the practical application of qualitative assessments for such accidents.

Limited information has been identified within the road and rail sectors. Some European countries have established risk criteria that consider consequence magnitude in terms of societal risk (F/N curves, see Figure 6 and Figure 7), but it remains unclear how these apply to very large consequences (disaster risks). This issue appears to be unexplored in the transport sector and has a low level of maturity.

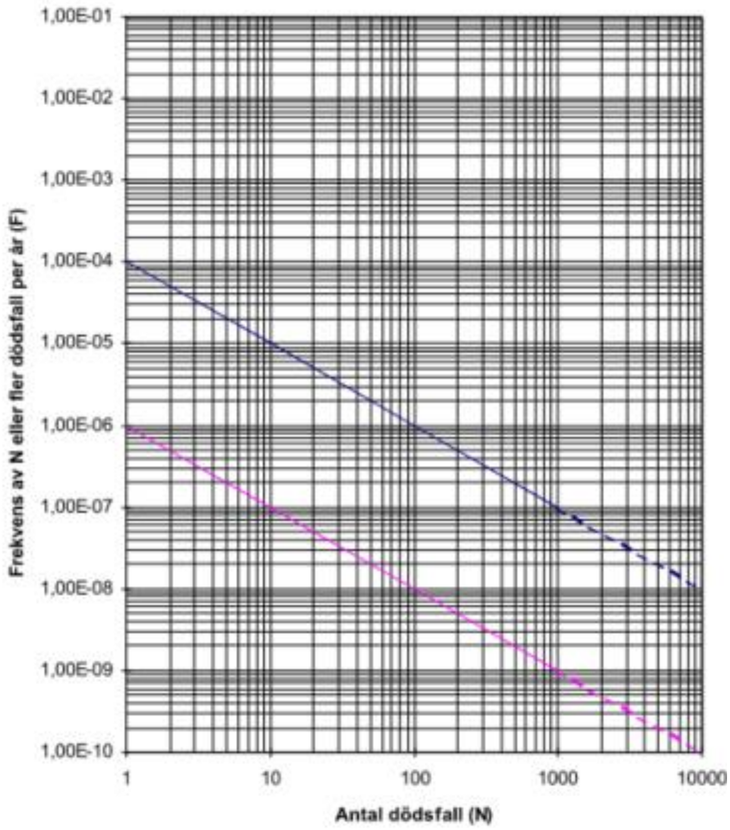


Figure 13. Country: Sweden, Sector: Physical Planning and Hazardous Activities. [8].

In the Swedish Transport Administration's Tunnel Construction Requirements (TRVINFRA-00233) [12], societal risk criteria are specified according to Figure 16. These assessment criteria apply to accident frequencies per train kilometre with consequences of up to N ≤ 1,000 fatalities. The Tunnel Construction Requirements also state that if the maximum potential consequence is estimated to exceed 1,000 fatalities, a project-specific safety target should be determined through a special investigation. However, no additional guidance is provided on how this special investigation should be conducted.

In the Swedish Transport Agency's Road Tunnel Safety Regulations TSFS 2022:13 [15], the acceptance level is presented in the form of FN-curves, as shown in Figure 9. These regulations include criteria for incidents with up to 10,000 fatalities.

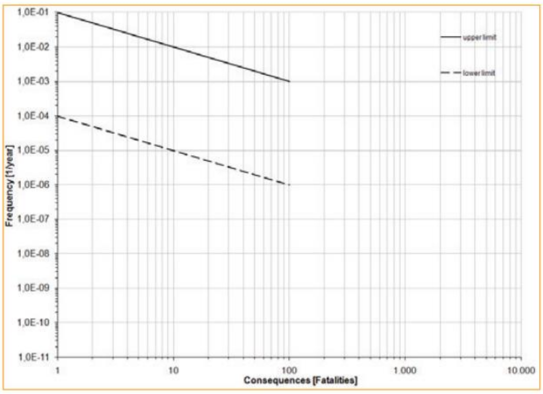


Figure 14. Country: Italy, Sector: Road Tunnels. [18]

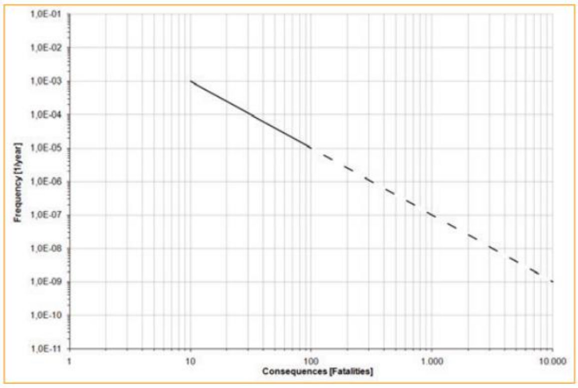


Figure 15. Country: Austria, Sector: Road Tunnels. [18]

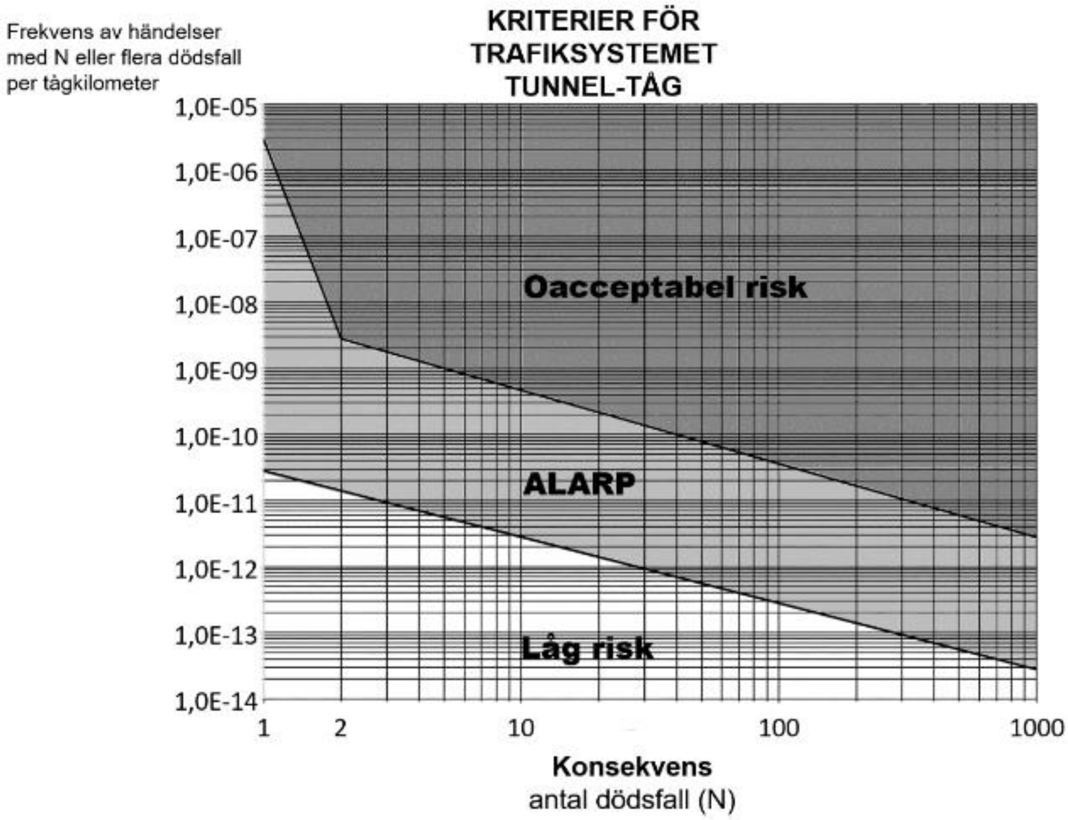


Figure 16. Societal risk criterion for individuals traveling by train in railway tunnels, from Trafikverket's Tunnel Construction Requirements regulations. [16]

The results of the presented examples show that risk criteria are exclusively reported as FN-curves, which were the most common measure found in the literature review. However, there are also risk criteria for certain industries expressed differently than FN-curves, such as in the nuclear sector, where criteria are defined as radiation levels in relation to distance from the facility. These types of criteria are considered challenging to apply within the transport sector and are therefore not presented in the graphs.

The concept of risk acceptability varies significantly between sectors and jurisdictions. While some industries, such as nuclear power, adopt rigid quantitative thresholds, other sectors rely more on qualitative assessments. Risk acceptance criteria are not absolute scientific truths but are shaped by societal values, political decisions, and historical experiences.

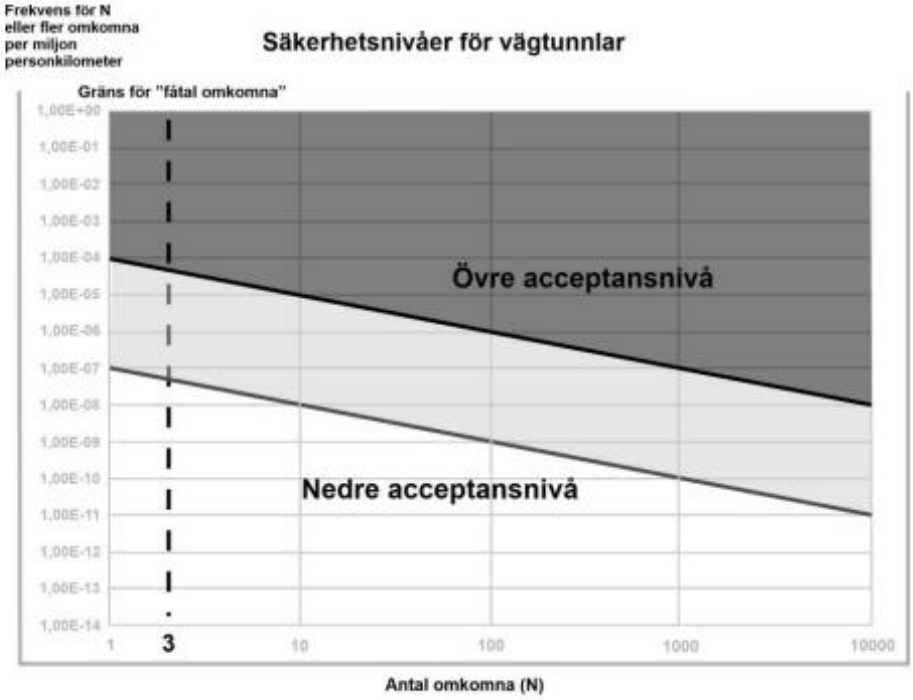


Figure 17. F/N diagram showing the upper and lower acceptance levels for road tunnels in the Swedish Transport Agency's regulations TSFS 2022:13. [17]

This study does not argue for a universal standard but rather examines how different regulatory approaches manage disaster risks. A balance must be struck between comparability across sectors and respecting national decision-making autonomy. The EU's directive on tunnel safety, for instance, encourages nations to develop their own provisions rather than enforcing a uniform threshold.

The findings reveal that quantitative risk acceptance criteria concerning consequence magnitude vary by industry/facility type and by country. There is no unified set of criteria applied consistently across sectors, whether in terms of curve slopes (risk aversion, curve position) or maximum allowable consequences. Based on these insights, the following section outlines key recommendations for enhancing disaster risk management in the transport sector. Additionally, variations exist regarding lower thresholds, i.e., areas where additional risk-reduction measures are not mandated even if they are cost-effective. It is important to note that the literature review does not provide a comprehensive overview of all risk acceptance criteria but does indicate the current level of knowledge.

There are examples where quantitative criteria impose no limits on the severity of allowable accidents, and conversely, where the presence of disaster risks renders the activity unacceptable. Some criteria specify that the potential for large consequences requires stricter application of ALARP (As Low As Reasonably Practicable) and intense scrutiny, often permitting such risks only under exceptional circumstances. For instance, exceptional circumstances may apply if the risk exists only temporarily, such as while permanent risk-reduction measures are being implemented. When no other options are feasible, operational limitations such as restrictions may need to be thoroughly examined [19].

In some dam safety charts, risks are only acceptable under exceptional circumstances, such as wartime, where the government may determine acceptability if societal benefits are deemed significant. The rationale for establishing a threshold on the maximum acceptable damage in risk acceptance criteria relates both to clarifying when additional assessment is required and to signalling an unwillingness to introduce new, more extensive catastrophic scenarios into society. Such a threshold is not dictated by natural law but is instead a practice established in some fields, while unused in others. Management tends to be binary; that is, either a distinction is made for very large accidents, or it is not. In all situations where the need for special treatment is identified in the acceptance criteria, >1,000 fatalities represent the scale at which such requirements are applied.

Thus, a clear recommendation regarding the limitation or allowance of disaster risks based on regulations and guidance from other countries and industries cannot be made. No single established methodology exists for constructing such curves, with approaches varying across sectors and countries. However, it appears appropriate that specific investigation and assessment should be undertaken in these cases, and that general guidelines for conducting such assessments and structuring decision support (in terms of both content and quality) should be developed. It is also reasonable to consider whether such risks should be accepted before there are established rules to limit them, and under what conditions, and to determine who should assess their acceptability. This is especially challenging within infrastructure compared to geographically isolated facilities, as measures like limiting freight transport capacity can have impacts on the whole transport system that extend beyond the scope of a specific project. In practice, this can mean that such decisions cannot be made within a specific project, even if the measure itself may be reasonable from a broader perspective.

Conclusions from the Literature Review
The literature review led to several key conclusions:

- Explicit requirements are set for managing "disaster risks" through risk analysis, regardless of consequence size.
- Decisions on risk-reducing measures are made using risk-informed decision-making, where risk analysis and "quantitative criteria" are part of the decision-making basis.
- Requirements for disaster risk management are not solely based on "quantitative criteria" or technical standards for facilities.
- Prescriptive requirements include a subset of necessary requirements for addressing "disaster risks."
- ALARP is present in some form across all studied examples.
- Collaboration with emergency services, including emergency planning, is a critical component of the requirements for risk reduction.
- In several areas, allowing activities with large potential consequences is not self-evident, which is also reflected in quantitative criteria.
- Requirements for risk reduction include both preventive and damage-limiting measures.
- Safety requirements, especially for preventing catastrophic incidents, have a strong reactive element.
- The transport sector's requirements in this area are relatively underdeveloped compared to high-hazard industries.
- Incidents with extensive casualties are (fortunately) rare, so strategies for managing disaster risks cannot rely mainly on empirical data or past event experience.

There are also examples of different regulations for existing facilities versus new developments, where higher risks are tolerated for existing activities, but new disaster risks must not be introduced in new developments.

EXPERIENCE WITH DEFINING DISASTER RISK CRITERIA FOR UNDERGROUND FACILITIES

In Sweden, there is limited experience with explicitly defining criteria for disaster risks involving high-consequence scenarios in underground facilities. Currently, two projects in the railway sector have examined this issue in greater depth, with proposed criteria developed by the infrastructure manager. One project involves a partially covered platform area along the Huvudsta–Duvbo section of the Mälarbanan line near Sundbyberg, while the other is at Stockholm Central Station, where plans include covering part of the rail area with an overbuilding. These projects are at different planning stages and have not yet been finalized or approved for operation by the Swedish Transport Agency.

There are existing facilities with similar platform conditions in operation, but at the time of their development, general knowledge and requirements for managing risks associated with hazardous goods transportation were different, and disaster risks were not explicitly addressed in the planning processes. Consequently, these examples will not be highlighted or discussed here.

Mälarbanan - Sundbyberg Station

In the risk assessment for Sundbyberg Station, it was determined that there is a very low but not negligible probability of an accident with a potentially large number of fatalities (over 1,000 fatalities). Individuals at Sundbyberg Station were classified as passengers and included in the safety assessment calculations for the Sundbyberg Tunnel. In the event of a major accident with dangerous goods at the station or tunnel exit, people at the station could also be affected and potentially fatally injured. These individuals were therefore considered in the risk assessment for the tunnel.

It was also noted that there is no widely accepted criterion or procedure for evaluating incidents with over 1,000 fatalities within either the Swedish Transport Administration's own regulations or those of other authorities. This lack of clear criteria created uncertainty in managing the situation, as the proposed facility design allowed limited flexibility for risk reduction without exceeding the project's scope. Consequently, a project-specific risk evaluation was conducted based on the following elements:

- Examination of assumptions, causes, and frequencies for high-consequence scenarios.
- Comparison of PLL (Potential Loss of Life) values with other rail tunnels in Sweden.
- Review of possible measures to reduce the risk of major accidents.
- Management of uncertainties.
- Consideration of the facility's societal benefits, including sustainability, capacity enhancement, urban development, and third-party risk reduction.

The overall assessment concluded that the risk could be accepted based on the extremely low frequency of severe accidents, the project's net reduction in societal risk for third parties, and acceptable individual risk levels for passengers and third parties. Furthermore, the Mälarbanan expansion is expected to provide significant societal benefits by increasing transport capacity and supporting urban development in Solna and Sundbyberg. The railway plan for this section has been approved by the Stockholm County Administrative Board and submitted for planning review by the Swedish Transport Administration.

Stockholm Central Station / Centralstaden

Another project recognizing the risk of a single accident affecting a large number of people is the planned covering of Stockholm Central Station. This project, known as Centralstaden, includes development with high rise buildings on top of the covered platform area. Currently in the detailed planning stage, the proposed design is set to undergo public consultation in 2025. As the facility will include both an underground station and overhead development, separate acceptance criteria have been established for risks above and below the covering. This study focuses on the risk acceptance criteria for the spaces under the covering, i.e. the platform area, which have been developed in a project memo by the Swedish Transport Administration [20].

The criteria state: "The safety level in the platform area under the covering structure should be comparable to that of other modern platform enclosure. Comparable platform enclosure include those designed or built in Västlänken, Citybanan, and suitable stations where freight trains pass. Trafikverket recommends using the future Sundbyberg Station as a reference."

Given that dangerous goods do not pass through Västlänken or Citybanan, Sundbyberg is the primary reference point for comparing disaster risk aspects. As this underground station represents the first example in this paper, no alternative methods for disaster risk assessment are added.

A separate risk assessment approach has also been prepared for safety above the covering, led by the Stockholm City Building Office. The basis for assessing risks around and above the covering includes the following components:

- Risk Profile
    - As catastrophic potential is inherent, a deeper analysis should focus on this to improve knowledge and reduce uncertainties.
    - Other unique risk profile characteristics impacting the needs of barriers should be identified.
    - The risk profile will guide the depth and scope of further analysis.
- Barriers
    - Both technical/physical and organizational barriers are considered essential for safety throughout the system.
    - Different types of barriers are evaluated, including those within the rail facility, other parts of the planning area, readiness of on-site actors, and societal crisis preparedness.
    - Barriers should be possible to regulate and verify over time.

In this risk assessment, the unacceptable risk threshold is extrapolated with an unchanged slope into the area exceeding 1,000 fatalities. However, there is no designated zone for more than 1,000 fatalities where risk is considered directly acceptable. Therefore, in cases where potential catastrophic scenarios are identified, as is the case for the Centralstaden area, a detailed analysis of scenarios and barriers is always required to determine if the risk level is tolerable. These analyses are proposed in three sequential steps: (1) barrier identification, (2) barrier analysis, and (3) safety assessment.
For incidents with catastrophic potential, no definition exists for a directly acceptable risk level, meaning the assessment basis does not specify the exact barriers required to achieve an acceptable risk. Instead, decision-makers are expected to evaluate this by reviewing different barrier combinations and their risk-reducing effects, including the responsibility distribution among involved actors. Additionally, the assessment basis specifies that barrier selection should consider factors such as risk reduction, safety level, and the acceptability of associated uncertainties. In summary, the assessment framework demands a more robust decision basis than is typical for physical planning risk evaluations, but it still leaves decision-makers in a challenging situation with limited guidance on what is considered reasonable.

These case studies illustrate the practical challenges of implementing disaster risk criteria in infrastructure projects. They highlight the need for clearer regulatory guidance and structured decision-making processes to ensure consistent risk management practices.

2. DISCUSSION

Lack of Consensus in the Literature

The knowledge base for regulating disaster risk in the transport sector is limited. This work suggests initial steps towards such regulation, but further research and development are necessary to establish effective standards. Evaluating disaster risks and deciding on suitable risk-reduction measures is a knowledge area that currently lacks sufficient answers to identified challenges. This gap increases the risk that the analysis and implementation of effective preventive measures may be overlooked in projects, potentially embedding vulnerabilities that could have been mitigated through proactive action.

There is no consensus among countries or sectors on what constitutes acceptable, tolerable, or permissible risk exposure. This also applies to low-probability events with the potential for mass casualties, i.e., events with disaster risk potential. Moreover, scientific literature provides little support for ignoring disaster risk simply due to low probability. Across industries, no such risks are deliberately left unaddressed.

While guidelines and regulations for disaster risk management exist in other sectors, few examples have been identified within the transport sector. One reason may be that unrestricted dangerous goods transportations through underground platform enclosure is rare or prohibited. Although certain European countries have criteria for road tunnels involving major accidents, the transport sector's standards are relatively underdeveloped compared to other sectors. Specific criteria for platform enclosure have not been identified.

The Existence of Disaster risks
Whether a facility poses a disaster risk depends on factors not fully regulated by the Planning and Building Act. The Swedish Transport Agency should determine if, and under what conditions, it is permissible to design facilities with disaster risk potential as described in this study. Not allowing such designs could impact transportation efficiency, while allowing them may introduce disaster risks.

Project Experiences
In Sweden, some projects have acknowledged the potential for high-casualty incidents in platform enclosure and attempted to assess disaster risks. However, risk assessment remains vague, leaving project-level decision-makers to determine acceptability. Despite this, identified disaster risks have not halted project planning.

Establishing clear safety targets helps prevent Black Swan events—low-probability, high-impact incidents often overlooked in traditional risk models. By integrating disaster risk scenarios into infrastructure planning, extreme but plausible events are addressed early, opening for reducing unforeseen disasters explicitly.

Rather than dismissing these risks due to low probability or political sensitivity, a structured framework offers two rational approaches: (1) designing resilient systems that mitigate their impact or (2) prohibiting intolerable risks outright. Defining and regulating disaster risks does not impose unnecessary constraints but enables informed decision-making, ensuring that extreme events are neither ignored nor implicitly accepted through regulatory gaps. Neglecting this increases the likelihood of true Black Swan events, not because they are unpredictable, but because they were avoidably overlooked.

Decision-Making Responsibility
Certain sectors, like dam safety, permit disaster risks but elevate decision-making to higher political levels, emphasizing that such decisions are exceptional and require careful investigation and scrutiny. The appropriate division of responsibility for the transport sector in Sweden is not discussed further here, but ought to be revisited by authorities having jurisdiction.

Need to Supplement Basic Standards
The basic standard (prescriptive requirements) for accidents with multiple fatalities provides a baseline safety level, but it is unclear if this is sufficient. Additional analysis of the need for risk-reduction measures for accidents covered by proposed safety targets, such as FN-curves, is necessary for complex platform enclosure. Basic standards are primarily derived from empirical data, so supplementary requirements for disaster risk management are needed, especially for rare and high-consequence events. This includes understanding potential scenarios and exploring risk-reduction options, complemented by requirements for facility design—such as redundancy, approach to untested solutions, and safety system maintenance.

Control over Risk-Reduction Measures
Reducing disaster risks, for instance in dangerous goods transport, can be challenging, as some risk-reduction measures lie outside project-specific infrastructure design, e.g., tunnels and platform enclosure. Restriction on transportation of certain substances is one such example. Determining if measures outside facility design are necessary to ensure acceptable risk levels within the Planning and Building Act is complex.

Clarity on facility requirements, including any external measures, would help avoid sub-optimization and uncertainty in operational safety.

Balancing Interests

Decisions to reduce disaster risk inherently require balancing multiple interests. Who makes these trade-offs and how significantly impacts the outcomes. This should be factored into regulations for disaster risk management.

The suitability of constructing infrastructure, including tunnels and/or platform enclosure with disaster risk potential, requires deeper investigation and is not solely a matter of engineering or scientific judgment. Until clearer guidance exists, strict investigation requirements should be in place if such facilities are permitted at all.

Disaster risk Threshold
Platform enclosure may, under certain circumstances, pose a risk of high-casualty incidents. If such designs are to be allowed, specific requirements for managing these risks should be developed. Existing design methods, aimed at other types of accidents, may not provide adequate protection. The 1,000-fatality threshold serves as a rough indicator for incidents requiring additional risk management. Other countries and sectors use similar thresholds, reflecting a limit above which incidents are either prohibited or require additional scrutiny.

Low-Probability Dismissal
In some cases, arguments suggest that disaster risks can be accepted if the probability of occurrence is sufficiently low. However, scientific literature provides very limited support for this rationale. Even with a low probability, the risk contribution of a scenario cannot be fully understood without examining the potential magnitude of its consequences [19]. If an activity could lead to a catastrophic scenario, it may not necessarily align with sustainable urban development and might require alternative design approaches or may not be permissible at all. However, certain aspects of societal development mean that some level of risk to human life cannot be entirely avoided, including within infrastructure systems or in large facilities like stadiums or hospitals.

The Need for a Holistic Approach
Disaster risk management, like safety management, requires standards across multiple system components, which interact in design and operation. However, regulations often target specific parts of the safety management system or facility, missing the overall system functionality. To address this, it is essential to clarify how different system components interconnect and how requirements relate across domains.

Decisions on disaster risk acceptance may depend on both facility design and infrastructure management systems. The interface between these two is challenging to address in standards and regulations.

Role of Emergency Services
The role of emergency services presents challenges in setting facility requirements. Emergency personnel must be able to safely operate in complex environments like underground platform enclosure, but their operational capacity can sometimes vary between different regions and municipalities. Consistent requirements for factors like distances, water supply, and evacuation sites are needed to create safe operational conditions. Simultaneously, emergency services need to practice in such facilities to ensure readiness, though mandating this in regulations is challenging.

Need for Guidance
Due to the lack of guidance on evaluating disaster risks, significant project-level differences are likely conducting these assessments. It is worth investigating whether disaster risks align with long-term, sustainable infrastructure planning, and, if so, how to determine adequate risk management. Consideration should also be given to which authority decides acceptability and the principles governing such decisions.

Evaluating Disaster risks
If incidents with extensive casualties are to be managed effectively, certain aspects require further study and clear standards for evaluation and decision-making. Leaving these complex assessments to individual projects may not reach optimal results. Furthermore, "creeping vulnerability" may be introduced as infrastructure, once built, is difficult to modify. A low-probability scenario may be viewed as plausible over the system's lifespan, particularly as system configurations and risk

perceptions evolve. An unnoticed increase in vulnerability may only become apparent upon catastrophe, threatening society's functionality and safety.

ALARP and cost-benefit analyses often guide these decisions, but this approach has challenges. Highly improbable events with large impacts may be undervalued compared to certain, immediate benefits. Rational decisions may be difficult when costs, risks, and benefits are distributed among multiple actors, and uncertainty is high.

The challenges of safety through quantitative risk assessment and cost-benefit decisions are recognized. These tools, while part of a broader decision basis, are insufficient alone. Therefore, additional considerations must be included in regulations.

Introducing risk-informed decision-making requirements in current standards could help clarify the need for additional factors in risk assessments. For example, refining "comprehensive assessment" criteria and integrating risk-informed decision-making could enhance clarity and effectiveness.

Need for Improved Decision Support

Disaster risks in underground platform enclosure require more than technical standards; requirements for training, preparedness, and safety management systems are also essential. Quantitative criteria alone are insufficient; risk-informed decision-making considers additional aspects, including safety margins, barrier properties, uncertainty, cost-effectiveness, and decision quality. Control over disaster risks requires regulatory focus on these elements.

In addition to technical standards for disaster risks, operational requirements are needed to ensure effective disaster response. Design-stage decisions impact operational safety, necessitating alignment between design and operation.

RECOMMENDATIONS FOR THE TRANSPORT SECTOR

The following recommendations are derived from the study's findings and aim to provide policymakers with practical measures for strengthening disaster risk governance in the transport sector. These recommendations do not propose a universal methodology but highlight key areas where regulatory improvements can enhance safety outcomes. Based on the findings presented in this study, the following recommendations outline key steps to improve disaster risk governance in the Swedish transport sector.

1. Develop sector-specific risk acceptance criteria:
   - Introduce explicit risk criteria for catastrophic events in underground transportation infrastructure, drawing on methodologies from other sectors (e.g., nuclear and dam safety).
   - Establish guidelines for when FN-curves should be used and how they should be interpreted in transport context.
2. Strengthen risk assessment methodologies:
   - Require transport infrastructure projects to integrate both probabilistic risk models and qualitative assessments to account for uncertainties and decision-making under incomplete information.
   - Introduce scenario-based stress tests for underground stations and tunnels to evaluate worst-case scenarios and response capacities.
3. Clarify the division of responsibilities between regulators and project developers:
   - Define clear regulatory requirements for when special investigations must be conducted for projects involving potential disaster risks.

  - Ensure that decision-making responsibility for high-impact risks is elevated to an appropriate policy level, rather than being determined solely within individual projects.

4. Introduce regulatory refinements based on international best practices:
   - Explore the application of ALARP (As Low As Reasonably Practicable) or de minimis thresholds in transport safety regulations.
   - Consider implementing adaptive regulatory approaches that allow flexibility in risk acceptance depending on specific project conditions.
5. Operational requirements and periodic evaluations:
   - Regular risk assessments should be conducted at least every five years, and emergency response exercises should involve relevant stakeholders, including the fire and rescue services.
   - Ensure that risk assessments are well-documented, include uncertainty analysis, and provide clear justifications for accepted risks and trade-offs.

By implementing these recommendations, the Swedish transport sector can adopt a more structured and consistent approach to disaster risk management. These proposals are grounded in the study's findings and provide a framework for improving regulatory consistency and safety outcomes. The following section summarizes the key insights from this research, reinforcing the basis for these recommendations.

CONCLUSIONS AND SUGGESTED DIRECTION

This section provides a synthesis of the study's key insights, summarizing the empirical findings and their implications for transport risk governance. This study has examined the governance of disaster risks in underground transportation infrastructure by analyzing regulatory frameworks across multiple sectors and jurisdictions. The findings highlight several key insights:

- Sectoral differences in risk governance: Industries such as nuclear power and dam safety have well-defined risk acceptance criteria for catastrophic events, whereas the transport sector has yet to develop an equally systematic approach.
- Fragmented regulatory landscape: Existing Swedish regulations lack a unified framework for addressing disaster risks in underground transportation, leaving risk assessment methodologies inconsistent across different projects.
- Need for risk-informed decision-making: Effective disaster risk management requires a combination of quantitative approaches (e.g., FN-curves) and qualitative considerations, including epistemic uncertainty and societal values.
- No universal methodology for disaster risk assessment: Regulatory approaches vary significantly across industries and countries, suggesting that solutions must be sector-specific and context-sensitive rather than relying on rigidly applied global standards.
- Regulatory responsibility: A key question remains whether the Swedish Transport Agency should regulate disaster risks at the national level or leave such decisions to project-specific assessments.

These insights provide a foundation for further regulatory improvements and future research on disaster risk governance.

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