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Tunnel fire safety management and systems thinking: Adapting engineering practice through regulations and education

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ABSTRACT

Society is changing ever faster, and tunnels are complex systems where performance is affected by many different stakeholders. These conditions suggest that safety management needs to be proactive and based on a systems perspective that acknowledges socio-technical theories. Although systems thinking principles are foundational in overarching European regulations and goals, system principles generally don't affect tunnel fire safety design principles or engineering practice. In the countries investigated in this study, tunnel fire safety management (TFSM) builds on experience-based and risk management-based principles that are optimized independently system by system. This is usually done with limited consideration of how these systems are interconnected and affect the overall tunnel system. The purpose of this paper is to investigate how systems thinking could support existing engineering practice. The work presented in this article is the outcome of a collaboration between fire safety researchers and practitioners from five countries and three continents. Through three workshops, current TFSM principles have been compiled and discussed. It is suggested that tunnel safety regulations be redesigned to strengthen the ability of engineers to work in design teams using systems thinking principles.

1. Introduction

1.1. Safety engineering and management principles

The aim of tunnel fire safety management (TFSM) is to protect societal values such as life, health, property, environment, and key societal functions from fire. Safety includes all measures and arrangements intended to reduce or prevent losses of these values. International tunnel safety rules and regulations emphasize means for self-rescue, ventilation, and fire resistance. Most countries also specify overall goals and visions, for example the Vision Zero [1,2], which is a vision of no fatalities or serious injuries in the transport system. Overall visions and goals are further specified in principles assumed in the design process, higher-level principles such as enforced self-regulation, co-operation, and universal design, which all need approaches to express, analyze and interpret the level of fulfilment. These principles are seen as fundamental for tunnel fire safety. The regulatory regimes vary from adopting prescriptive and detailed requirements to enhancing performance-based requirements specifying the function or purpose, which entails fundamentally different safety management strategies by the involved actors.

TFSM consists of all efforts, actions and measures taken to prevent fires and protect societal values from fires in tunnels. Sound engineering practice might adapt to Kletz' [3] characteristics of a friendly plant. A priority might be *intensification* by developing safer concepts than single-bore bi-directional tunnels. However, other tunnel design aspects, such as length, slope, curvature, and intersections, will also compromise safety. *Substitution* addresses careful selection of materials, and together with *attenuation and limitation of effects* contribute to an *inherently safer design*. The preparedness measures, such as technical passive and active fire protection systems, and other technical safety information and management systems must be organized in accordance with the *simplification* characteristics. Fire mitigation needs to be designed to avoid *knock-on effects*, which includes safe distance between vehicles involved in fire scenarios. The emergency response systems and road user

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behavior and responses in tunnel fires must be *tolerant* and contribute to a *clear situation status* for all involved parties. In general, the system of systems must allow *ease of control* to bring the necessary assumptions of systems safety thinking into play.

In a systems thinking perspective, safety is produced by the interactions of involved actors and safety measures. Lack of appropriate interactions, or lack of control over important processes, may lead to system states that allow accidents to happen. In 1997, the European commission stated that road causalities should be seen as “failures in complex systems of human decisions and actions, a variety of infrastructures and all kinds of vehicles” [4]. In 2001, after experiencing the tragic outcomes of the Mont Blanc and Tauern tunnel fires, the United Nations Economic and Social Council’s expert group on safety in road tunnels presented recommendations to improve European tunnel safety. The recommendations were organized under the categories 1) road users, 2) operation, 3) infrastructure and 4) vehicles [5]. This work, along with preceding and parallel development in European countries, notably France [6,7], led to the realization of the Directive 2004/54/EC. Generally, the Directive has been instrumental in strengthening tunnel safety work in Europe through a combination of regulation principles. The Directive specifies minimum requirements (solutions) to road tunnels on the TEN-T network, while also being inherently risk-based and founded on a systems perspective. Safety regulation principles are discussed in section 1.2. Even though a systems perspective is acknowledged in higher-level management principles, such as the Vision Zero, and European regulations, such as Directive 2004/54/EC, a *systems approach* to tunnel safety engineering and management is not adopted in the Nordic countries.

In Fig. 1 two prevailing management strategies within tunnel safety management are depicted: prescription of experience-based solutions and risk management. We have also added systems thinking as a third pillar. Fig. 1 indicates that these management approaches will co-exist and serve complementary purposes for TFSM. On that premise, it is interesting to understand the logic underpinning each approach, and to discuss the interplay between education, regulation, and practical fire safety management (FSM), whether the perspective is tunnel planning, design, or operation.

The aim of this paper is to discuss and provide ideas on how to develop a more systems-oriented approach to TFSM, which would be more in line with visions, goals, and European *trans*-national tunnel safety regulations. The discussion and ideas build on current approaches to TFSM, exemplified through narratives from five selected countries: the UK, Sweden, Norway, Australia, and the USA. Regulatory regimes, academia, and engineering practice are challenged. The sample of countries is explained in the Method section. The term TFSM refers to comprehensive fire safety issues from planning and design to maintenance and operation. The hypothesis was that the current situation in the selected countries is characterized by routinized compliance-based safety work, which underestimates active future-oriented fire safety management. If the hypothesis is true, TFSM might unconsciously drift towards and beyond safety constraints (safety envelope) that could lead to catastrophic events [8].

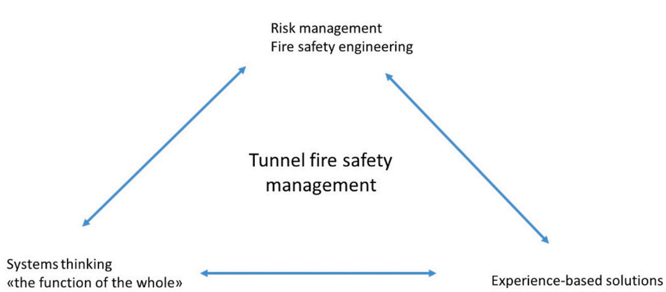

Fig. 1. Fire safety planning, design, and operation as a mixture of three different management approaches.

1.2. Safety regulation principles

A historical view on TFSM reveals that it has been incrementally developed through trial and error. Consequently, it is natural that an experience-based approach to solutions of geometries and safety systems has a strong position among both the regulators and regulated. Experience-based solutions tend to become manifestations of what is considered as safe, and there is effectively no separation between safety as a system property and safety as a specific set of measures, which is a barrier to innovation and development [9]. TFSM is bound by the regulation regimes that have developed in the last 30 years mirroring the construction industry, some major fire events, and various national practices.

Transport tunnels represent a major loss potential in case of accidents. New energy carriers and digital technology are transforming tunnel systems, adding unprecedented challenges and opportunities relative to existing safety regulation regimes. There is a need to understand the limitations of existing regulatory regimes and the corresponding engineering and management practices to identify possible changes that may improve the situation.

The Transportation Research Board [9] classifies regulatory regimes along the means-goals axis and the micro-macro-axis. As a result, there are four archetypes (A1-A4) of regulatory principles, which are illustrated in Fig. 2.

A1 is sometimes referred to as “the prescriptive” regulatory regime. This is somewhat misleading, since A3 also includes prescription of specific means through the regulation. The major difference is that A1 *prescribes solutions and/or products* (micro level), while A3 *prescribes management processes* (macro level). A1 is thus closely associated with safety management through application of experience-based solutions or prescription of safety products. A2 is referred to as the performance-based regime where the regulation specifies micro-level goals to achieve, without specifying solutions or products. A3 is the “management-based” regime, sometimes confused with “the performance-based” or “functionally based” regime. A4 is referred to as general duty/liability, which relies on specifying high-level goals and ex-post tort law, i.e., punishing the violator after accidents. The Vision Zero philosophy may be regarded as a macro-goal regime (A4).

It is the task of national regulators to design a regulatory regime by selecting or combining regulatory principles. The selection of regulation principles and/or combination of principles depends on three main factors [9], addressed as core questions:

1) **Nature of the safety problems:** How to balance frequent and small accidents versus low probability and major loss potential? How well or poorly understood are the causes of hazards and undesired events? Are there trusted interventions against the safety problem? Is the safety problem static or dynamic in nature?
2) **Industry characteristics:** Are private incentives aligned with regulatory goals? Are the regulated parties a homogeneous or heterogeneous group (size, resources, knowledge)? What is the degree of variation in activities and operations in the sector? What is the degree of technological diversity and rate of change?
3) **Regulatory capabilities:** What is the level of legal authority towards industry? How sensitive is the regulatory work to public and

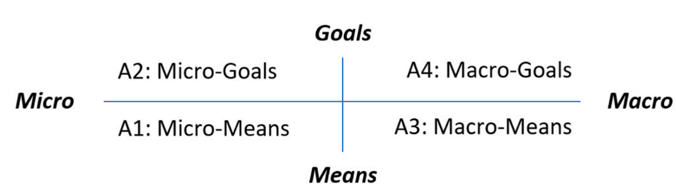

Fig. 2. Archetypes of regulatory regimes.

political expectations? What are the administrative and procedural constraints? Which budgetary resources are provided? What is the human capital and hiring flexibility? How much time is available to develop the necessary competence for effective supervision?

Regulations are the overarching tool that influences the weight to be put on, for example, systems safety thinking. The balance is of vital importance in the following analysis of engineering practices and regulatory premises in the five countries represented here. A systemic approach is clearly stated in Annex 1 of the European Directive, where article 1.1.1 reads: "Safety measures to be implemented in a tunnel shall be based on a systematic consideration of all aspects of the system composed of the infrastructure, operation, users and vehicles." The Directive also prescribes a risk-based approach, while also specifying minimum requirements. Hence, the Directive seeks to obtain the appropriate balance by combining regulatory principles A1 and A3.

Developing micro means is generally a way of integrating experiences. The use of micro means has been adopted from the civil engineering industry and the close connection between the tunneling industry and the building industry are important premises for interpreting current TFSM. Performance-based requirements for the building industry was developed during the 1990s. This approach was transferred from other sectors, such as energy and chemical industries. Risk and reliability analyses were identified as tools to address performance-based requirements. These tools became integrated into fire safety engineering, through which the practical fire safety engineer applied elements from both performance-based thinking as well as experience-based thinking [10]. Comparative fire safety analyses became the preferred tools to determine whether micro goals (alternative solutions) were as safe as prescribed micro means. Since the beginning of the century, many countries use probabilistic risk analysis to show that tunnels achieve acceptable risk levels, and some countries include elements of systems thinking, for instance France [10] and the Netherlands [8].

France [11] builds on the UNECE expert group's [5] notion that a tunnel is a complex system in which its components interact and have to be coordinated in order to enhance safety. According to Deffayet [11], this fundamental understanding was instrumental to the development of French TFSM, specified through a Technical Instruction (TI). The TI specifies a prescriptive TFSM approach, where the choice of safety measures depends on several system variables. There is also the option of reaching an equivalent safety level by other means, where the prescriptive TI serves as the reference level of acceptable safety. Like Directive 2004/54/EC, the French approach combines regulation principles A1 and A3.

Ruland et al. [12,13] describes a Dutch TFSM approach based on systems engineering principles. The development of a new approach was motivated by delays and budget overruns in previous tunnel projects, attributed to validation issues between the design and operational phase. To improve interactions, the approach builds on explicitly stating functional requirements, system modeling, stakeholder involvement and operational issues in the design phase. This method implicitly includes elements of systems thinking and represents an interesting step towards integrating systems thinking in a practical engineering framework.

1.3. Systems thinking for safety management

Modern safety management, founded on the mentioned high-level principles, acknowledges that safety is a system property, which emerges from the interaction of the involved actors and technical subsystems. For instance, Vision Zero shares many traits with systems thinking in the sense that accidents are perceived as a system property and it is a shared responsibility of all stakeholders to keep the system within the safety constraints [1]. System designers must ensure that the road system (roads, vehicles and users) are either inherently safe, i.e. eliminate errors, or at least fail-safe, i.e. forgiving of errors such that the exerted violence on the human body is tolerable [2,14]. However, it is difficult to see any impact from the Vision Zero on tunnel fire safety design [15]; much more could be done in this regard.

In a dynamic environment the hazard sources, their control requirements, and sources of disturbances change frequently. According to Rasmussen [16,17], by the year 2000 we faced a period of technological change, deregulation, fierce competition, and increasing public concern. This change has increased even more since the beginning of the century. Charles Perrow [18] discusses the manageability of systems based on the axes *coupling* (from loose to tight) and *interactions* (from linear to complex). Back in 1984, motor vehicles were Perrow's example of a *linear and loose system*. This means that the systems are rather predictable and manageable, and failures/accidents do not easily escalate beyond their physical origin.

Development towards a greener future involves introduction of new energy carriers, such as ammonia, hydrogen and electrical batteries, which introduces new hazards to tunnel systems [19]. Increased efficiency of transport systems is important to improve sustainability, which drives digitalization of transport systems. New possibilities arise with 5G internet solutions and data processing power, including the introduction of autonomous vehicles and generally increased use of artificial intelligence agents as part of the transport system. Consequently, the functionality of future tunnel systems will, due to stronger interconnectedness, become increasingly dependent on other safety critical infrastructures, such as power supply, internet and cloud services for data storage and processing. The number of involved actors will increase, and increased efficiency implies increasing traffic loads.

Future transport systems will be increasingly coupled to other systems and the interactions will be increasingly complex. Following the arguments of Perrow [18], increased complexity reduces the stakeholder's ability to predict events and performance levels that might endanger tunnel safety and security. On the other hand, increased complexity is a byproduct of increased functionality, which also could improve safety and security in transport systems. In this environment, risk management cannot be based solely on static models or responses to past incidents but must be increasingly proactive [20]. Socio-technical systems (STS) theories aim to understand how institutions, actors and technologies interact, which is necessary for proactive risk management in an increasingly complex and dynamic society [16,17]. Risk management must apply an adaptive, closed loop feedback control strategy, grounded in the information flow among decision makers at all relevant levels of society. Due to human flexibility and creative intellectual powers, a human organization possesses particular potential for such adaptive control. Thus, it is argued that a systems thinking perspective is important in future TFSM.

Checkland [21] defines systems thinking as the process of thinking using systems ideas. He further defines a system as the abstract concept of connected elements that constitutes "a whole". An intuitive parallel is organisms that can adapt and survive, within limits, in a changing environment. Arguably, a tunnel can be seen as a whole consisting of several integrated parts. Two pairs of ideas are foundational to systems thinking: 1) *hierarchy and emergent properties,* and 2) *communication and control*. *Hierarchy* implies that all systems have a layered structure, consisting of sub-systems, units, and parts. Systems are also part of a system of systems. The definition of "the system" is thus relative to the context in which the system is studied. The system has properties that are *emergent* on a specific level of the hierarchy. Tunnel life safety, for instance, is a property which is emergent on a rather high hierarchical level. It is meaningless to talk about life safety of road users and merely include the tunnel construction. Instead, we would need to take into consideration, for instance, the tunnel construction, safety equipment in the tunnel, the vehicles, communication systems to/from the tunnel and the tunnel control center. The local fire and rescue service might also be included in the "system" but may also be included in "the system of systems", i.e., the level above the entity in which we are interested. An emergent property on a lower level might be a sprinkler system's ability to *suppress* a fire or its *reliability*, i.e., probability of functioning on demand.

If an entity is to survive in a changing environment it must have processes of communication and control. It needs mechanisms to adapt to changes and hazards that arise. Communication channels between the interconnected sub-systems, units, and parts within the system are needed to pass on information to understand the status of ongoing processes within the system. However, understanding the status of ongoing processes is of limited value if there are no means of *controlling* the behavior of the processes. In general, we can say that the safety of a system is maintained by higher-level system elements imposing safety constraints on lower-level elements, which govern the freedom of behavior of the lower-level elements. Safety within systems thinking effectively becomes a control problem [22]. Tunnels are complex systems within the transport infrastructure, which are subjected to hierarchical management showing emergent properties, that enables efficient communication and controls. TFSM could be improved and adapted to the tunnel's latent conditions by adopting systems thinking.

2. Method

The primary aim of this work is to answer this question: H*ow can TFSM adapt to systems thinking and how can such a development be* integrated *into academia, practice, and regulation?*

Given the fast pace of changes to transport systems there is a need to understand the limitations of existing regulatory regimes, the corresponding engineering and management practices, and the need to identify possible changes that may improve the situation. Regulation regimes must be considered for its ability to promote holistic introduction of systems thinking.

The work presented in this article is the outcome of a collaboration between fire safety researchers and practitioners from five countries and three continents. Such a collaboration is at the core of the approaches taken by the Norwegian Research Council to invoke cross country collaborations to enhance understanding and innovation in complex systems [23]. The involved researchers and their respective countries represent an interesting background for our analysis. For instance, Norway is one of the world's most tunnel intensive countries and has a long history of tunnelling. The country is also known for innovative safety management from the oil & gas industry. The UK and Sweden have been active within tunnel fire safety research and fire dynamics for decades, while the number of tunnels in these countries is modest. Australia has been a frontrunner on performance-based fire safety regulations in the construction industry. Australian tunneling is a rather young industry but the construction of tunnels has grown rapidly the last decades. The US is interesting for its federal regulatory system and impact on standardization, notably through the work of the National Fire Protection Association on tunnel fire safety.

Through three workshops, current TFSM practices have been compiled and discussed and narratives were developed that describe the relevant historical context, regulations, and practices of TFSM in the five countries highlighted in this study. The first workshop was devoted to safety theory, including post normal science [24–26], a systems perspective [21,27], adaptive risk management [16,17] and safety engineering [20,28]. All participants have an overview of a vast amount of literature and are themselves responsible for many publications in the subject area. This knowledge is an added asset to the analyses conducted.

The second workshop was devoted to current TFSM regulation and practice in the five countries. The participant's involvement in practical engineering processes as well as various scientific studies were included. The tunnel fire safety regulations were reviewed by the participants from each country resided.

The third workshop included a brainstorming session about future developments directed towards an increased systems theory approach to TFSM. The participants agreed that the analysis of the relations between the three different approaches in Fig. 1 must challenge the notion of important features being a barrier or a driver of TFSM moving towards an enhanced use of systems thinking. Therefore, 18 topics that related to TFSM and systems thinking were prepared for the third workshop, of which the following five were selected by voting at the workshop:

- Overall design processes and fire safety integration
- Tunnel system definition and problem framing
- FSM education programs (formal competence of fire safety engineers)
- Total competence of fire safety engineers (including continuous professional development)
- Competence of design team

These five topics were consequently discussed with regards to the current practice and suggestions for future developments. The data from the workshop have been transcribed and made available for broad analysis for bringing TFSM a step further. The data analysis consisted of three steps.

Firstly, current regulations were assessed against engineering practices to reveal gaps and characteristics within TFSM. The regulatory principles are important to a future adaptation to systems thinking.

Secondly, the safety systems applied in various tunnels, on roads and rail, were addressed to understand their functions in a holistic system. The justifications of the fire safety systems of the five countries were compared to understand why they varied so much. Furthermore, the emergence of various fire safety systems were related to the country's attitudes to innovation in the tunneling industry.

Thirdly, the authors created a set of measures various actors must consider if they wish to formalize systems thinking as a more visible approach to TFSM. This set of measures is raised with the intention to discuss how academia, the engineering and construction community, tunnel owners and the regulators must be challenged to impose changes. Resistance to change is probably the most difficult barrier to overcome in the future.

3. Tunnels and planning processes – narratives from five countries

This section aims to describe the extent of rail and road tunnels, the major purposes of the tunnels, the frame conditions for the tunnel designs and to provide a critical review of TFSM in the UK, Sweden, Norway, Australia, and the USA. Each subsection reflects the researcher's judgment about which issues to highlight to give a short introduction to the country's approach to tunnels and safety planning.

3.1. UK

In the UK, road tunnels tend to be considered only for river crossings (Tyne Tunnel East [1.7 km], opened in 2011; Silvertown Tunnel [1.4 km], due to open in 2025; Lower Thames Crossing [4.2 km], proposed), or to avoid disruption to areas of natural beauty or historic importance (Weston Hills Tunnel [230 m], opened in 2006; Hindhead Tunnel [1.8 km], opened in 2011; Stonehenge Tunnel [4 km], proposed). Also recently opened is the Airside Road Tunnel [1.4 km] within London Heathrow Airport. The need for tunnels is generally an accessibility issue that resolves traffic off main roads at the outskirts of cities. Typically, these tunnels are two lanes per tube, unidirectional tunnels with a mix of passenger vehicles and heavy goods vehicles. In many instances, transport of dangerous goods is permitted. Except in specific cases like the Heathrow Airside Road Tunnel, most tunnels will carry a high average daily traffic load. There is no apparent trend towards urban tunnels, as seen in many other countries.

Until 2020, design of road tunnels in the UK was covered by the guidance of BD 78/99. In March 2020, a new guidance document, CD352[1], was introduced to replace BD 78/99. This document is published by Highways England but is adopted as guidance for all motorways and trunk roads in the devolved nations within the UK as well. This document is considered to be a design standard, sitting below the Road Tunnel Safety Regulations (2007).

The primary fire safety concept employed for road tunnels is self-rescue, and tunnel safety systems are provided to achieve this, for instance the main function of the emergency ventilation system is to ensure a tenable environment for self-rescue of tunnel users on foot.

For rail tunnels in the UK, the current standard used is BS 9992–2020, which recommends a mixture of prescriptive and performance-based requirements, replicating in most instances the minimum requirements set out in the European 'Technical Specification for Interoperability – Safety in Railway Tunnels' (TSI SRT). Natural ventilation can be permitted, based on 'engineering analysis', but certain requirements for maximum and minimum airflow, and a minimum 2 h of operation during an emergency are prescribed if mechanical ventilation is employed. For structural fire protection it is also a 2 h resistance requirement against the ISO 834 time-temperature curve for passenger only train tunnels, and 2 h resistance to the EUREKA (RABT) time-temperature curve[2] for tunnels with goods traffic. Egress from rail tunnels is designed using a self-rescue concept, as with road tunnels. Various provisions are recommended to ensure safe egress, including, e.g., cross passages between tubes in twin tube tunnels at least every 500 m. Much of the life safety guidance is informed by BS 9999–2017, the design standard for fire safety in buildings. As with road tunnels, design decisions for rail tunnels are made by a stakeholder group, who review the design and construction process and agree early in the design stages how risk analysis will be applied to the project and the criteria by which risk analysis will be accepted. While 'As low as reasonably practicable (ALARP)' terminology is not used in BS 9992, the concept of practicability is well embedded within the standard. Following the UK's withdrawal from the EU, which entails withdrawal from compliance with EU guidance, a National Technical Specification Notice (NTSN) on Safety in Railway Tunnels was published in January 2021, the requirements of which do not deviate from the specifications of the TSI SRT.

The Channel Tunnel between the UK and France adopts its own fire and life safety policy, which relies on an assisted rescue strategy, with passengers being guided by train staff to a place of safety in the event of a fire, rather than self-rescue. The Channel Tunnel also employs a novel firefighting strategy, whereby trains are driven to designated water-mist suppression zones in the event of a fire. In a worst-case scenario, this could entail a train with a fire being driven up to 15 km through the tunnel before reaching one of the water-mist zones.

3.2. Sweden

Sweden has nearly 200 transport tunnels among which 45 are road tunnels and about 60 are railway tunnels at least 500 m long. Most tunnels have been built during the last 30 years. Recently, Sweden has been constructing many urban road tunnels that are typically twin-tube tunnels with 2–3 lanes and uni-directional traffic in each tube, e.g., the Northern [3.6 km] and Southern link [4.6 km] in Stockholm. Some of the largest road tunnels in Europe, the Bypass Stockholm tunnels, are being constructed with 18 km of tunnels and safety equipment such as Fixed Fire Fighting Systems (FFFS). These road tunnels mainly aim to resolve traffic issues within cities, but to some extent also address regional and national needs. Railway tunnels are built both in cities and in rural areas. For example, eight single railway track tunnels were built on the Botniabanan [1–6 km] in the rural north of Sweden. In the south, new high-speed railway tracks are proposed and planned between Stockholm, Gothenburg, and Malmö. Tunnel configurations considered in modern rail tunnel projects call for a selection between double track tunnels with a parallel service tunnel or two single track tunnels to ensure safe evacuation and means for rescue service response.

Planning and construction of road and rail projects are principally regulated in the Road and Rail Acts, the Environmental Code, and the Planning and Building Act. In the Road and Rail Act the planning process is outlined, including requirements for consultation with agencies, municipalities, the public and other stakeholders. The Act on Protection against Accidents is applicable in the operational phase and regulates the obligations of organizations and persons to prevent and manage accidents, including fires. In addition to these laws that deal with fire safety in a general manner, there are also specific road and rail tunnel fire safety regulations.

A fundamentally important difference between the regulations applying to road and rail systems is that the TSI SRT and the minimum requirements regarding safety in rail tunnels have the status of EU regulations, which means they are a law in Sweden. A directive, such as the one on Minimum Safety Requirements for Tunnels in the Trans-European Road Network (2004/54/EC) must be incorporated into Swedish law (hence law 2006:418). The common safety methods (CSM RA) regulation (Commission Implementing Regulation (EU) 402/2013) is central when it comes to risk management of all types of technical, operational, or organizational changes in the railway system that have an impact on safety and when a risk assessment is required according to the TSI SRT. At the lowest formal regulatory level, the Swedish Transport Agency has issued mandatory provisions on safety in road tunnels that further specify the minimum level of safety (TSFS 2019:93 & TSFS 2022:13). The TSFS provisions require that each tunnel longer than 500 m should have a safety officer who shall coordinate all preventive measures and safeguards to ensure the safety of users and operational staff. The Swedish Transport Administration (STA) has developed its own road and rail tunnel design guides to facilitate the management of tunnel construction projects since the 1990s. Similarly, the regulations on safety in rail tunnels builds on TSI SRT.

Fire safety design starts early in the planning process where a safety concept is established. The safety concept includes the means for self-rescue. Fire safety engineers are included in the planning phase either as employees or consultants to the tunnel developer. During the design phase, fire safety is one of many design branches where fire safety engineers are tasked with fire safety design aspects such as means for evacuation and rescue service intervention. Maintenance and retrofit of operational tunnels are managed in a similar way to new construction.

Risk management is a central activity throughout the planning and design stages. Many qualitative and quantitative risk analyses are performed. Risk management concerned with tunnel-specific accidents is regulated in the TSI SRT, CSM RA, Environmental Code, national tunnel safety regulation and through internal guidelines from the STA. CSM RA states three principles for risk acceptance: use of accepted practice, comparison with similar systems or an explicit risk assessment. In case of risk assessment, upper and lower acceptance criteria in F/N diagrams are prescribed for quantitative risk assessment in rail (TRVINFRA-00233) and road (TSFS 2022:13) tunnels. The risk assessment criteria include an ALARP region, where further safety measures should be evaluated by a cost-benefit assessment. Another purpose of risk management is to ensure coherence from planning and design to construction and operation, i.e., to ensure that risks are managed and that no risks or safety concepts are misinterpreted when they are handed over, e.g., from the design stage to construction or operation, or from one design branch to another. This is mainly achieved by design documentation and the actions of the safety officer (for road tunnels) who coordinates the risk management activities. In addition, several prescriptive requirements must be fulfilled.

[1] https://www.standardsforhighways.co.uk/prod/attachments/987a669b-13a1-40b9-94da-1ea4e4604fdd.

[2] See Rail Industry Guidance Note GIGN7619 www.rssb.co.uk.

Some recent tunnel projects in Sweden have had good collaborations between STA, manufacturers, consultants and the research community that have resulted in new solutions, e.g. FFFS [29,30] and egress guidance [31] being implemented, and trade-offs being made. In practice there are several examples of performance-based thinking in how STA apply their own design guide and prescriptive requirements. There is an increased willingness to apply trade-offs between different safety systems, e.g., lowered requirements on passive protection if FFFS is installed.

3.3. Norway

Norwegian tunnel history is important when considering tunnel FSE and management practices. Tunnels have presented a variety of transport challenges in Norway since the first railway tunnels were constructed in the late 1800s [32]. Currently, there are more than 1200 road tunnels [33] and 700 railway tunnels [34] in operation in the country. Many tunnels are solutions to difficult topography. Other tunnels are risk reducing measures in areas exposed to natural hazards, such as snow avalanches, rock falls and landslides. On weather-exposed mountain passes, tunnels improve the availability of the transport corridor. In coastal areas, with fisheries and other export industries, tunnels provide a dependable connection to mainland Norway and the industry's international markets. Several Norwegian tunnels reduce barriers in geographical housing and labor markets, allowing a decentralized population and meaningful activities in major parts of the country. In urban areas tunnels resolve accessibility issues and transit traffic through cities. Tunnels are built to make space available for housing and economic activity, reduce noise and other pollutants from transport, and reduce barriers for pedestrians and cyclists. In agricultural areas, tunnels can help preserve areas which are important for food production.

The first Norwegian design manuals specifically directed at fire safety in railway and road tunnels emerged in the early 1990s. They contributed to increased standardization of technical solutions and convergence towards European safety standards. Since then, there have been small incremental improvements in safety solutions, until the major European fire accidents in the late 1990s and early 2000s, and the following EU directive on road tunnels in 2004. Railway tunnels are governed by TSI SRT and Norwegian Technical Rules. The major fire events and sudden improvements of safety standards in road tunnels have affected the opinion and debate about railway tunnel safety as well. The current situation is characterized by a rather extreme number of tunnels and major leaps in safety standards between older (pre 1990s) and newer tunnels (post 1990s and especially tunnels planned after 2007). To level these leaps in safety standards would, first and foremost, be extremely expensive, but also technically and operationally challenging.

The *National Transport Plan* (NTP) reflects the sitting government's political prioritizing of transport projects in the coming decade, based on input from the public agencies on roads, rail, maritime and aviation. Prioritized transport projects enter the formal planning process, which follows a regime specified by the Norwegian *planning and building act*. The process is highly iterative, starting with the development of a broad planning program and increasing the level of detail through several phases and decision gates. Decision making related to land use is decentralized. Municipalities affected by the transport project have a major impact on transport corridors and overall concept selections, e.g., the selection between a road concept including tunnels, versus a concept that includes no tunnels. In a few cases, for nationally important transport projects, the local democracy is overtaken by a central governmental land-use plan. For the design of tunnels, the planners need to adhere to the Norwegian Road/Rail Act and the Tunnel Safety Regulation. This is similar to the Swedish process, but one major difference is that fire safety is not a separate design branch; it is a part of other design branches such as construction and electricity. Basic principles for tunnel design are:

- Enforced self-regulation and Vision Zero states that each tunnel owner needs to ensure safety, e.g., via risk analysis or systems safety analysis.
- The self-rescue principle prevails.
- A universal design that should consider disabled persons.
- Cooperation principle: Tunnel owners and actors such as the fire and rescue service need to cooperate to deal with tunnel fire safety, emergencies, and fire safety management.

The regulation lacks a holistic hierarchy of goals, functional requirements, and prescriptive solutions. It is better described as a patchwork of different types of regulations, with a strong foundation on prescribed technical solutions (micro-means). The Norwegian Public Road Administration have their own design regulation for tunnels longer than 500 m, *N 500 Road Tunnels*, which applies a classification from A to F depending on the average annual daily traffic (AADT) (traffic volume) and tunnel length. Different prescriptive requirements, e.g., maximum distance between emergency doors or a separate escape tunnel, are dependent on the classification. In addition, there are some performance requirements (macro-goals), for instance for fire protection of the construction, and some management-based (macro-means) requirements for risk and preparedness analysis. For instance, it is a requirement that risk assessments of road tunnels are conducted during the design phase for all tunnels. An emergency preparedness assessment is mandatory for tunnels longer than 1000 m. An influential guide for risk assessment, *TS 2007–11 Guidance for risk analysis of road tunnels*, was developed by the NPRA in 2007. Projects have been launched to increase the status and process of the risk assessment in practice, as prescriptive solutions have a strong foothold, both within authorities and industry. It is difficult for pioneers trying to take a more performance-based approach to come up with innovative solutions to Norwegian tunnel safety challenges.

Since 2011, there have been several serious road tunnel fires, e.g. the Oslofjord [35,36] and Gudvanga fires [37,38]. No persons have died because of these fires, but they have raised political, academic and professional debates about safety levels and pinpointed several specific challenges related to compliance with the self-rescue principle, given the Norwegian design and operational practice.

This acknowledgement has led to some changes, such as: increased usage of video surveillance for better situational awareness, better information systems to notify road users (loudspeakers), improved wayfinding systems (emergency lighting), and research into how the self-rescue principle could be maintained, with special emphasis on the use of evacuation rooms/shelters [39–42].

Fire safety management in road and rail tunnel design and operation is characterized by standardized processes and compliance-based thinking. Risk and performance analyses are tools to support chosen designs, and if no major fire incident occurs it seems that this practice will continue.

3.4. Australia

Australia is currently in an infrastructure development boom. Tunnels are a major component to tackle transport congestion in major cities and enhance overall network efficiency and productivity [43]. According to Taheri & Karlovsek [44], 9 out of the 12 largest ongoing infrastructure projects in 2019 were tunnel projects, either for railway (train and metro) or road transport purposes. By 2025, the total number of tunnel lane kilometers in operation will increase by over 100 %, with most of the projects being delivered in the urban areas of Sydney and Melbourne [45].

Major road tunnels are limited in number and a recent phenomenon, but increasingly relevant in Australia. Casey [45] includes a list of 28 road tunnels that represent tunnels longer than 300 m in Australia. 11 of these long tunnels are classified as "major" road tunnels and account for approximately 70 % of the annual vehicle kilometers travelled in road tunnels in Australia. The major road tunnels have the following characteristics: uni-directional traffic, longer than 1 km, located in an urban area and dangerous goods vehicles are not allowed. Common fire safety measures include fixed firefighting system (deluge), hydrant system, hand-held extinguishers, hose reels, tunnel ventilation, emergency egress passages, CCTV, public address system, radio re-broadcast and emergency service radio networks [45]. The Sydney Harbour tunnel, constructed in 1992, is the oldest of the major tunnels.

Austroads states that, during the past decade, the "Safe System approach" is implemented as a fundamental principle for road safety in Australia. The Safe System approach resembles the Vision Zero principle in Sweden and Norway, as it aims for zero deaths and serious injuries and takes "a holistic view of the road transport system and the interactions amongst the roads, the roadside environment, travel speeds, vehicles and road users" [43].

There is a difference between how tunnel fire safety should work in theory, and the way it is done in practice. This is inherent to the way Australian legislation works. Australia has a national tunnel fire safety standard, AS-4825-2011. This standard is intended to provide a generic framework for establishing the fire safety systems that are required in road, rail, or bus tunnels to provide an acceptable level of safety in case of fire. The standard is intended to guide professional fire safety engineers in the development of a fire safety strategy, and the design and documentation of fire safety systems for tunnels. However, the standard mainly prescribes a set of fire safety systems, and it is in general very easy to comply with the standard. The standard defines appropriate performance on safety systems, but the systems can be combined in various ways which offers huge freedom for the designers.

There is no national legislation or regulation for tunnel fire safety in Australia, instead each State has its own regulation. These rules are structured around a Ministerial Framework. There will be a minister which is the State Department of Transport and Main Roads that sets up the specific rules for each state. In general, the rules should comply with the Australian Standard, but since it is very easy to comply with this standard, the real design requirements are defined in the tender document by the State Department of Transport and Main Roads. When a specific tunnel is to be built, the state procures a builder based on a tender document called Scope of Works and Technical Contract (SWTC). The SWTC requirements tend to be extremely detailed, invoking many global approaches such as NFPA standards. Generally, it will include the characterization of a design fire, depending on the classification of traffic. Thus, a set of design fires are prescribed against which the tunnel needs to be designed.

Some requirements, e.g., ventilation requirements, are often defined using performance-based approaches based on CFD analysis etc. Egress is also based on performance-based requirements, prescribed design fires and advanced analysis. For other fire safety concerns, e.g., fire resistance, a prescriptive approach is taken with prescribed time-temperature curves. Detection solutions are generally stated as mandatory detailed prescriptive requirements ("you shall have"). Often a sprinkler solution is prescribed in the same manner ("you shall have"). At the end there will be consultation with the local fire brigades, but this is consultative and not statutory. In the end it is the State Department of Transport and Main Roads that approve the design based on the SWTC.

The Australian approach does not consider all layers of fire protection as an ensemble, therefore, when implemented, there is the potential for inconsistencies and overlaps among the different measures. In a system of this nature there are no overarching goals of safety that allow for different combinations of solutions, but instead the performance targets each individual system utilized. Thus, in some ways, the application of specific fire protection measures is treated as a constraint.

3.5. USA

There are more than 500 roadway tunnels [46] and 210 railway tunnels [47] in the USA, through which thousands of passengers and millions of USD in goods are transported on a daily basis. Many of the roadway tunnels were constructed in two distinct periods of highway expansion [48], the first taking place during the 1930s and 1940s as part of the Great Depression era public works programs, and the second coming during the development of the Interstate Highway System throughout the 1950s and 1960s. Construction continues, in some cases with significant and complex systems, such as the depression of major roadways through Boston, Massachusetts, in the late 1990s through early 2000s [49]. Similarly, there is a long history of rail tunnels in the USA. Although many were built in the 20th Century, some still operating railway tunnels date to the 1800s, with several currently under construction [50]. Subway systems in Boston, Massachusetts, where the Tremont Street subway opened in 1897 as North America's first subway tunnel [51] and New York City, where the first subway line opened in1904 [52] have the oldest operating transit tunnels. The 2nd Avenue subway line in New York City, which is still under construction, is the most recent subway tunnel project in the city [53].

As in other countries, tunnel projects in the USA are complex and require much planning and coordination. Projects typically begin with scoping studies, require environmental impact analysis, and production of a 'technical requirements' report, which outlines design and regulatory requirements. A sense of the complexity and timing required for roadway tunnel projects and for rail tunnel projects can be obtained by viewing [49,53,54], respectively. A significant part of the complexity in the USA is the fact that there are several responsible parties, legislation and regulations, and standards and guidelines that impact any given project. Whereas the USA is governed under a federal system, there is a combination of federal, state, and local legislation, regulation, and responsibility. Furthermore, responsibilities may be divided amongst entities depending on the form of transit.

For example, relevant actors include:

- US Department of Transportation
  - Federal Highway Transportation Administration (roadway tunnels)
  - Federal Railroad Administration (interstate train systems)
  - Federal Transit Administration (light rail and subway systems)
- US Environmental Protection Agency
  - Environmental Impact Analysis (EIA) and Environmental Impact Statements (EIS) required.
- State and local level Departments of Transportation, Environmental Protection, and Transit
- Industry/professional associations, e.g.,
  - AASHTO (The American Association of State Highway and Transportation Officials)
  - ASCE (American Association of Civil Engineers)
  - NFPA (National Fire Protection Association)

In general, legislation enables regulation, and regulation cites standards and guidelines, similar to other countries. However, in the USA, there is an Executive Order that requires consensus standards to be used, when they exist for the purpose, instead of creating new regulations specific to a federal agency [55]. As such, many federal regulations cite standards developed by industry/professional associations/standards developing organizations, including AASHTO, ASCE, NFPA and others.

This leads to another important distinction with respect to most other countries in that fire safety requirements for tunnels in federal and state regulations largely point to requirements contained within NFPA standards. The NFPA 502 standard for road tunnels includes fire protection and fire life safety requirements. In particular, NFPA 130 addresses fire safety in passenger rail systems and includes tunnels, among other things, and NFPA 502 addresses fire safety in road tunnels.

The NFPA develops standards using a consensus approach [56]. Technical Committees [TCs] develop draft documents, which ultimately go before the membership for approval. TCs often are comprised of a number of practicing engineers that use the standard, as well as a number of authority representatives, e.g., the rescue service, and often materials and systems manufacturers, insurance representatives, and researchers. Since the standards that are developed are largely technical documents, the TC deliberations can often be technical discussions about revised wordings and design numbers, e.g., how to calculate the critical velocity or tabulated number intervals for different design fires. In general this is a challenge with any consensus-based standards development process [57,58]. A systems-theoretical approach would bring broader discussions into the committee work.

As for the design process, the NFPA standards, while prescriptive in nature, tend to point out the need for holistic or systems approaches. NFPA 502, for example, provides a specified set of factors that should be considered "as part of a holistic multidisciplinary engineering analysis of the fire protection and life safety requirements" (paragraph 4.3.1). This is a form of systems thinking; however, the limitation to 'engineering analysis' may mean that critical actors and perspectives are missing from the discussion and decisions.

Commentary in the annexes note that the engineering analysis should be used to guide the decision process by the stakeholders and the authority having jurisdiction (AHJ) for implementation of specific fire protection and life safety requirements, and that the engineering analysis might, for some facilities, involve conducting a fire risk assessment that identifies the potential fire hazards and the consequential risks imposed by those hazards on the facility and its occupants. It goes on to note that a fire risk assessment should be conducted as an adjunct to, and not a substitute for, qualified professional judgment, and that the content and the results of the fire risk assessment can be included in the emergency response plan documentation submitted to the AHJ. It further notes that a fire risk assessment can also include a quantification of risks that can be used to inform a performance-based approach to safety, and in some circumstances, it might be appropriate to use a fire risk assessment to inform aspects of the design of the facility.

The commentary goes on to state that where a fire risk assessment is used, risk acceptance criteria should be used. Risk acceptance criteria can be categorized as either "absolute" or "comparative." Absolute risk acceptance criteria should be generally specified on a case-by-case basis by relevant authorities or predetermined by regulation, while comparative risk acceptance criteria should demonstrate that the proposed facility design provides a level of risk equivalent to or better than a reference facility.

A key issue of NFPA 502 concerns the design of the ventilation system. Smoke management should be implemented after the detection of a fire to provide a tenable environment during the various emergency phases. So called 'technical trade-off' is to some extent considered in NFPA 502, 2023 edition; "Passive fire protection is designed to reduce the heat flux to the tunnel wall. This reduction in heat losses to the tunnel wall increases the load on the tunnel ventilation system and should be considered in its design. Fixed water-based fire-fighting systems reduce the heat release rate, and this should be considered in the design of the tunnel ventilation system." [NFPA 502, sect 7.1.2]

It should be noted that in addition to NFPA 502, the Transportation Research Board (TRB) has published guidance on smoke control in roadway tunnels, which is framed within a risk-informed approach [59]. The TRB has also published guidance on design fires for roadway tunnel design [60].

NFPA 130, 2023 edition, also takes a systems perspective stating that: "Fire safety of systems shall be achieved through a composite of facility design, operating equipment, hardware, procedures, and software subsystems that are integrated to protect life and property from the effects of fire. […] The level of fire safety desired for the whole system shall be achieved by integrating the required levels for each subsystem." [NFPA 130, Sect 4.1] The stated goal is to provide a fire safe environment for occupants based on the following measures: Protection of occupants not intimate with the initial fire development; and, maximizing the survivability of occupants intimate with the initial fire development.

NFPA 130 furthermore makes a distinction between combustible and noncombustible materials stating that the intent of the standard is "to provide minimum requirements for those instances where noncombustible materials are not used due to other consideration in the design and construction of the system elements" [NFPA 130, sect 4.2].

4. Safety challenges and solutions – experiences from five countries

In this section, similarities, and differences between the five countries are illustrated from the perspective of a set of common fire safety management measures for tunnels. The goal is to highlight different national preferences for safety systems, as well as different regulative and engineering practices. The sections are a synthesis based on inputs from the researcher's national perspectives.

4.1. Fire resistance and load-bearing capacity in the event of fire

Fire resistance is an important component in all tunnel safety regulations. The main goal of this requirement is that the load-bearing capacity of the tunnel is maintained during (and beyond) the event of fire. A partial or full collapse could lead to time consuming reparations or refurbishments which, from a socio-economic perspective, can be very expensive. Furthermore, risk of falling rocks or spalling of concrete in case of fires need to be considered, such that evacuees and the rescue service would not be exposed to falling debris.

In the countries studied, the common regulation principle to fire safety is the performance-based approach (micro-goals) by specifying the goal that the construction and/or protection material must achieve. In Sweden parts of the structure that are sensitive for failure, e.g., due to poor rock quality, may need to handle 2–3 h fire exposure following the hydrocarbon (HC) curve. In Australia and Norway, a similar approach is taken. The structure's fire protection is an integral part of the overall load-bearing structural design process. For heat transfer calculations, fire consultants determine the thickness of the chosen protection system. They are instructed to account for the heat transfer exceeding the frame of the time-temperature curve. Norway also specifies a set of experience-based solutions (micro-means) in guidelines, such as the number of millimeters of spray concrete necessary to protect flammable insulation, water protection materials and load-bearing constructions.

For road tunnels in the UK, CD 352 takes a risk-based approach (macro-means) to passive structural fire protection. The requirements for passive fire protection, and the level of protection, are determined following a detailed risk analysis process, which considers factors such as the traffic volume, vehicle types, typical cargo loads, the ventilation conditions, the presence or absence of a fixed firefighting system, etc. This acknowledges to some degree systems thinking, in that the actions of a FFFS will probably reduce the severity of a vehicle fire, so less passive fire protection will be required for the structure. In other words, trade-offs are permitted. The guidance even explicitly permits using a cost-benefit analysis to omit structural protection in certain instances where the cost of repair to an unprotected fire damaged structure is deemed less than the cost of installation of a protection system. Having taken a non-prescriptive approach to passive fire protection in general, the CD 352 guidance then defers to BS EN 1993-1-2 for prescriptive requirements for protection of all exposed structural steelwork.

Rail tunnels in the UK take a more prescriptive approach to structural safety, following BS 9992–2020, which specifies minimum requirements for tunnel elements and protection systems, based on performance in standard furnace tests.

4.2. Arrangements for evacuation

According to Ingason [61], the maximum allowable distance between emergency exits vary significantly between guidelines in different countries, encompassing everything from 150 to 750 m in road tunnels and up to 1000 m in railway tunnels. These design values are in most cases based on a consensus of expert groups in each country. In addition, risk analysis is often required. For instance, in NFPA 502 the required spacing between emergency exits should not exceed 300 m and should be determined by an egress analysis such that a tenable environment is provided. The design fire scenario and criteria for tenability and time of tenability shall be established as part of the analytical approach.

Both Norway and Sweden apply the self-rescue principle (which could be seen as a safety constraint), however a difference is that in Sweden a design criterion on tenability exists, such as those listed in TRVINFRA-00233, sect 7.6.3.4.11, on incident heat radiation, temperature, toxic gases, and visibility, to be used in a risk-based approach. Norway applies a universal design principle that considers disabled persons. According to NFPA 502 the uncertainties of people's behavior in a fire event and of those who are unable to self-rescue should be considered. In addition, the emergency response plan should recognize the need to assist people who are unable to self-rescue. The US also follows guidance provided by the TRB for the design of safe egress in smoke filled tunnels [62].

Means for safe evacuation is one of the main safety objectives of the tunnel system. Despite this, it has not always been the case in practice, e.g., Mont-Blanc, Tauern, St. Gotthard tunnel fires in 1999–2001 or the more recent fires in Norway. Most countries include prescribed solutions (micro-means), such as maximum allowable distances between emergency exits, to regulate evacuation safety of tunnel users. Regulations tend to require additional risk analysis in special circumstances to verify that tenable conditions are achieved for evacuees (performance-based or micro-goals), and show that the risk is acceptable, or ALARP (management-based or macro-goals).

4.3. Ventilation

Ventilation systems are not mandatory in railway tunnels. Ventilation is often needed in road tunnels to keep air pollution levels down. For fire safety reasons, the TFSM regulations in Sweden specify that where congested traffic may occur in bi-directional or uni-directional tunnels, semi-transverse or transverse ventilation should be installed. For longer tunnels with a high amount of traffic, TSI SRT requires a transverse ventilation system. However, Sweden often makes an exemption from this requirement for uni-directional highway tunnels and uses longitudinal ventilation instead. For tunnels where a queue situation frequently occurs, this is argued to be handled by a FFFS.

Longitudinal ventilation is the practice in Norway. If there is a possibility for congested traffic, a risk assessment should be used to show that the longitudinal strategy is acceptable. If needed, compensatory measures should be implemented. The direction of smoke ventilation is normally pre-determined depending on where the nearest professional fire and rescue service is located. The idea is that rescue personnel can enter the tunnel supported by ventilation. This is not necessarily a good strategy for tunnel users in tunnels with bi-directional traffic or uni-directional tunnels with congested traffic or queues. The strategy may lead to people being trapped in the smoke on the downstream side of the fire, which was the experience in e.g. the Oslofjord tunnel fires in 2011 [36] and 2017 [35], the Gudvanga tunnel fires in 2013 [37] and 2015 [38] and the Fjærland tunnel fire in 2017 [63].

In NFPA 502 it is clearly specified that the initial smoke stratification should be maintained, i.e., low or no ventilation near the fire. For bi-directional road tunnels smoke extraction should also be considered. For uni-directional road tunnels a longitudinal ventilation system may be used. The purpose of the emergency ventilation is to facilitate evacuation and ease firefighting. A design scenario should be selected considering "the types of vehicles that are expected to use the tunnel and whether the tunnel is fitted with other life safety systems including, but not limited to, FFFS, detection systems, and activation systems, and whether the other life safety systems allow for mitigation of the design scenario" [NFPA 502, sect 11.4.2]. Design guidance can be found in Refs. [59,60,62].

Australia tends to follow international practice; therefore, solutions are most likely aligned to European or American approaches. Ventilation will most commonly be longitudinal and follow the approach that ventilation should enable egress but mainly support firefighting intervention.

In the UK, a handful of old road tunnels have semi-transverse ventilation systems, but for all new tunnels and tunnel refurbishments, longitudinal ventilation is usually preferred. The CD 352 guidance requires that ventilation be used to "create conditions whereby tunnel users can evacuate the tunnel safely, assuming rapid awareness of the incident occurrence", but does not specify if this entails maintenance of smoke stratification or avoidance of backlayering.

The BS 9992 standard for rail tunnels in the UK explicitly requires backlayering to be controlled upstream of a fire in longitudinally ventilated tunnels, and it acknowledges that stratification will be lost in the downstream direction. The use of ventilation appears to be intended to assist self-rescue, and the use of ventilation to assist firefighting is not discussed.

Provisions for smoke ventilation and smoke management is a matter of debate within safety science and engineering practice. There are obvious dilemmas to consider, especially associated with the most common solution: longitudinal ventilation systems. Smoke exposure at certain levels is both harmful and lethal, and longitudinal smoke ventilation has the potential of both limiting and increasing the smoke exposure of tunnel users. It is clear that all countries in this study include requirements for smoke ventilation in at least road tunnels. The requirements are typically micro-means-oriented, describing the specific solutions, i.e., longitudinal ventilation, ventilation direction etc., rather than specifying the goal. However, exceptions exist, where USA (NFPA) and UK (CD 352) specify micro-goals-oriented requirements in terms of describing the expected performance of the systems related to life safety of tunnel users and firefighting assistance.

4.4. Fixed Fire Fighting Systems

NFPA 502 offers a background to the use of FFFS in tunnels in annex E, which shows how the prescription and perception of FFFS has changed over time and in different parts of the world. FFFS was pioneered in Japan and has been used successfully for decades in, for example, Australia and Japan. In Australia FFFS are often a "shall have" requirement. In the EU and the US, FFFS has been accepted as a safety measure in transportation tunnels in recent years. The effectiveness of these systems has been demonstrated through multiple full-scale fire tests, and there has been a substantial amount of material published on the subject [e.g., 29, 30]. In Sweden FFFS (deluge water spray system) is considered an important measure to handle the combined event *fire and queue* in uni-directional road tunnels, i.e., a scenario from a risk-based FSM approach. A Swedish research and innovation project was launched to develop a cost-efficient system solution (micro-means) for tunnels which resulted in a new "best practice" design concept. The concept includes a single water pipe along the tunnel ceiling which provides good performance at low system cost.

In Norway FFFS are generally not used in tunnels. In 2012 the Norwegian Public Roads Administration (NPRA) reported findings from the internal research program *"Modern Road tunnels"*. NPRA acknowledges the positive effect that FFFS have on structural integrity and human safety in road tunnels, referring to results from fire tests and research results from the *UPTUN project*. Still, NPRA concludes that FFFS is not recommended in Norwegian tunnels based on *considerable costs*, *lack of practical experience with FFFS in tunnel environments* and *uncertainty associated with long-term operational stability* [60, p. 22]. Norway is a country where tunnels serve several purposes. Many tunnels are in rural areas, have a rather low traffic volume and lack permanent water supplies. Low temperatures are also a challenge to water-based systems for a large part of the year. It is natural that the cost-efficiency of FFFS needs thorough consideration, both for new tunnels and, not least, if considering retrofitting FFFS into existing tunnels. However, since 2012, Norway has experienced several serious fire events [see e.g., 61] that should suggest a review of previous experience-based knowledge. An international change in practices would provide further pressure on Norwegian tunnel owners.

In NFPA 502, the goal of an FFFS is: "to slow, stop, or reverse the fire growth rate or otherwise mitigate the impact of fire to improve tenability for tunnel occupants, […] and/or protect the major structural elements of a tunnel" [NFPA 502, sect 9.2.1]. According to NFPA 502, FFFS, when installed, impacts other design values, e.g., fire load for ventilation or time-temperature curve for load-bearing capacity. In NFPA 502 the FFFS is tested by an accredited independent third party against two scenarios; one shielded pool fire for which the system should cool the surroundings and one wood pallets fire that the system should control or suppress. An overview of FFFS for tunnels in the US, and elsewhere, is provided in Ref. [46].

FFFS are not common in tunnels in the UK. They are considered only in cases where the ventilation system is deemed incapable of providing adequate protection for safe egress of tunnel users. When FFFS are considered, their primary function is seen to be the reduction of fire heat release rate to assist the ventilation system in controlling the smoke from a fire. They are generally not considered a firefighting system or a fire protection system. FFFS was installed during construction of the 2nd Tyne Tunnel in 2011, and in the 2015 refurbishment of the Dartford Tunnels, no other road tunnels in the UK use FFFS. The Channel Tunnel between France and the UK has defined zones within the tunnels equipped with FFFS. The intention is that if a fire occurs, the train is driven to the next FFFS zone or out of the tunnel.

FFFS is framed very differently in the five countries, from mandatory in Australia to practically no support in Norway.

5. Education, regulation, and engineering practice in a systems-theoretical context

This section includes a discussion of findings from section 3 and 4 about regulation theory, in the context of barriers and drivers for systems-theoretical thinking in TFSM. The discussion presumes that systems-thinking has a role to play in the combination of experience-based and risk-based safety management principles, which is illustrated in Fig. 1.

A starting point is presented in the CD 352 guide document in the UK. The guide is not overly prescriptive, and generally takes a risk-informed and performance-based approach to the design of road tunnels for fire safety. It requires that a 'Tunnel Design and Safety Consultation Group' (TDSCG) be established at the outset of the design process, including representatives from the designers, contractors, operators, and emergency services, including the fire service. It is the responsibility of the TDSCG to carry out a full risk assessment of the tunnel and, based on this assessment, various safety measures will be required, or may be omitted. It is this group wthat decides what constitutes ALARP in the context of the tunnel, considering, for instance, that the cost of a safety measure is proportionate to the expected risk reduction. The establishment of the TDSCG provides a good foundation for systems thinking in tunnel projects as it seems clear that the group has a joint responsibility for the tunnel's safety level. The following sections explore how more practical systems thinking approaches can be introduced.

5.1. Barriers and drivers for systems-oriented regulations

From the description of design practice in the five countries informing this study, it becomes rather clear that effective systems-thinking is difficult to combine with a pure experience-based regulation regime. For instance, the fire safety subsystems described in section 4 are framed in particular ways in each of the five countries, which results in different perceived importance in relation to the overall goal of tunnel fire safety. In the USA the emphasis is on the design of the ventilation system. In Norway, many discussions revolve around the specific means for safe evacuation. In Sweden, the question of implementing a FFFS or not has lately become the key safety issue. In this sense, the overall goal of current TFSM is to a great extent framed as a matter of achieving a safe subsystem.

Regulation based on micro-means principles (experience-based solutions) has a strong tradition within safety management. It supports a compliance-based approach, rather than analytical and pro-active engineering efforts towards dynamic safety needs. A major concern is that this tradition supports a false assumption that tunnel fire safety could be achieved by compliance with a set of safety measures in regulations and handbooks. However, fire safety is achieved by a chain of measures that produce an appropriate fire safety strategy. This fire safety strategy delivers the overall objectives of fire safety for the tunnel. The tunnel itself is a unique (and uniquely complex) infrastructure where many different approaches to a fire safety strategy are possible. By assuming that independent compliance with specific safety measures will ensure the safety of the tunnel, the uniqueness of each tunnel and each fire safety strategy is ignored, and a degree of freedom to designers is eliminated, locking them into a list of components as the only possible solution. The assumption could work for standardized buildings where the fire safety strategy has already been optimized, but it is not possible for a "prototype". Many transport tunnels are prototypes and thus the fire safety engineer needs a degree of freedom to optimise the fire safety strategy. As a consequence, tunnels should be the remit of highly competent and experienced specialists. This assumption could be one reason why fire safety engineers are not well integrated in the design processes and viewed as a constraint that must be used to verify the design against regulation requirements. In Norway, FSE is not even a recognized separate discipline in tunnel projects.

Regulation principles based on specifying goals (micro-goals) or management principles (macro-means) lead to different thinking about TFSM in design processes. Such principles assume an analytical approach, as there is a clear separation between the concept of safety and the means to achieve safety, which requires some form of interpretation and analysis. This analysis shows that the micro-goals principles are common in all five countries, e.g., for designing fire protection for load-bearing and fire protective constructions. Although such regulations allow for selecting different solutions and products, they are nonetheless restrictive in the sense that TFSM is segregated into a set of micro-goals that need to be achieved. In a dynamic society one might be better served by acknowledging that there is uncertainty associated with the set of micro-goals. Specification of the necessary processes required to manage safety (macro-means) assumes that the tunnel fire safety manager or designer needs to adapt to a changing world. This might, for instance, lead to inclusion of new fire scenarios based on new energy carriers in vehicles, which both impact design processes and operational safety management of tunnels. The focus becomes an issue of producing risk and emergency preparedness analyses, and not how to use the analyses in operational management of tunnels. This is a compliance-based strategy, which is remote from the proactive safety thinking of systems performance. An effective control structure must continuously enforce safety constraints on the tunnel systems to maintain the various safety functions, whether they are related to design or operation, or whether they are on a high or low level in the system hierarchy.

Systems-thinking is supported by regulatory regimes that encourage holistic assessments, such as management-based principles. Still, there are similarities among different tunnels that call for standardization, where management-based principles become overly cumbersome and might lead to an inconsistent design and management practice. Standardization of solutions might also have an intrinsic value in tunnels, as it reduces the workload of tunnel managers and maintenance personnel, and the mental loads in preparing tunnel users for emergency situations. To maintain an effective regulation regime for TFSM it is necessary to strike the appropriate balance between the different regulation principles. The goal should be to conserve, maintain and develop relevant experience-based learning, direct analytical attention to specific and known hazards, while also keeping an open mind that new hazards and solutions will emerge in the tunnel system's interaction within a dynamic society. A solution might be to explicitly require that (fire) safety becomes a specific discipline in the design and operation of tunnels.

5.2. Barriers and drivers for systems-oriented education and competency of practitioners

Regulations are important to TFSM in different ways, as instruments for the authorities, and as frame conditions for practitioners. Changing regulations to better support systems-oriented thinking is necessary but not sufficient. The different regulation principles presume different competencies and knowledge bases. Furthermore, the different principles in Fig. 1 are supported by different academic traditions. It is possible to develop educational programs that support either one, or a balance. Any program will have its own strengths and weaknesses. However, the importance of education should not be underestimated. It can be argued that, at least in Sweden, the FSE education program contains a mixture of experience-based rules and risk management. This mirrors the situation for fire safety design of tunnels very well and suggests that there is a strong connection between education programs and engineering practice. A central question then becomes: how can academia and education programs better support systems-oriented thinking for TFSM?

A review of education programs and competency requirements for the five countries generally suggests that available courses and specific competency requirements are lacking. From a historical perspective this is natural, where TFSM has been a matter of compliance with prescribed experience-based solutions. This type of safety management sets few specific requirements for the educational system, and engineering and supervisory competency. Developing micro-means regulations is, however, a major task and requires a strong professional community on the regulator's side, especially related to the fields of statistics and accident investigations.

In general, there is a trend towards more goals-oriented regulations, which is also apparent in the field of tunnel fire safety. Introduction of performance requirements implies that engineers and supervisory authorities must relate to models and analytical techniques.

Systems-oriented safety management generally presumes a higher degree of inter-disciplinary collaboration. A fundamental challenge associated with inter-disciplinary knowledge is its situational or context-dependent nature. Consequently, it is difficult to develop textbooks, courses and models that capture this "inter-disciplinariness". A different way of looking at this would be to discuss and teach students how to develop good inter-disciplinary processes in the field of TFSM, and how different professionals should act in such processes to improve the outcome. This is not to say that individual professional competencies are unimportant, i.e., understanding fire dynamics, human behavior in crisis situations, etc., but improving the understanding that your individual professional knowledge is of little value if it is not effectively communicated to, and understood by, other professional disciplines. Current design processes are dominated by a set of professional disciplines based on how tunnel systems were built in the past. Systems-oriented thinking in the context of knowledge and competencies relevant for TFSM implies that traditional constellations are not taken for granted, but adapted based on the professional discussion. This causes challenges associated with existing value chains, business models, risk distribution and responsibilities in tunnel projects that are not straightforward to solve, but are nonetheless important to discuss.

5.3. Barriers and drivers for systems-oriented engineering practice

Roads and tunnels are complex open socio-technical systems [64], in which accidents are the result of the interactions, or lack thereof, between the involved humans, infrastructures and vehicles [4]. Directive 2004/54/EC presumes a systems-oriented and risk-based safety management approach. Deffayet [11] describes the French regulative practice, where systems principles are incorporated into a prescriptive design guide (micro-means), which allows for alternative designs based on comparative risk evaluations. Experiences from the five selected countries suggest that the design practice is more in line with reductionist principles. Tunnels are broken down into subsystems, and not treated as an integrated system (see examples of such subsystems in section 4). Traditional FSE suffers from 'silo thinking' that often fails to engage the breadth of stakeholders who define the expectations for tunnel designs and operation, and therefore can miss critical data on objectives to meet and design features to build around. Furthermore, the focus is narrow with a major focus on physical elements and the design task is framed as a technical problem, considering each system or objective one by one, e.g., ventilation or passive protection. The design task for the fire safety engineer relates to choices of methods, time-temperature curves, and often scenario analysis gives the boundary conditions.

A review of engineering practice for selected fire safety systems shows that strategy conflicts can occur when specific measures are required in all tunnels, e.g., fire ventilation systems. Recent tunnel fires in Norway illustrate that it remains unclear whether the ventilation system supports the broad set of safety goals in the event of fire. For instance, both Oslofjord in 2011 and Gudvanga in 2013 are examples of fires where the ventilation system limited, rather than increased, the possibility of self-rescue in favor of the fire and rescue service's efforts. Ventilation systems play an important role in TFSM, but there needs to be sufficient flexibility to find solutions and management strategies that support all the desired fire safety objectives.

Rigid micro-means regulations are challenging with regards to the technology that is already included in the regulations. It becomes problematic when relevant and effective technologies are indirectly prohibited from the market, which can be argued as the case with FFFS in Norway. The regulators, who rely heavily on experience-based regulations, lack experience with FFFS, which becomes an argument for not introducing such systems. Additionally, the authorities have taken a rather clear stand to this issue by stating that FFFS are not recommended in Norwegian tunnels [65]. Consequently, it becomes controversial, in a practical context, to suggest implementation of FFFS in tunnel projects (in Norway), and the possibility is not even discussed. This is problematic due to potential benefits of FFFS, which are illustrated by regulations and practice in other countries. For instance, the introduction of FFFS is used to support the decision to design for a reduced fire load, less fire protection measures and reduced consequences (downtime) after fires. Hence, introduction of FFFS is not a pure cost issue, but involves potential savings and benefits that are not being considered in Norwegian tunnel projects.

In Sweden, FFFS are now seen as a solution to scenarios where tunnel users are trapped in smoke (i.e., traffic standstill in unidirectional urban tunnels with longitudinal ventilation). It is interesting to note that a regularly occurring challenge associated with queues in contemporary Swedish tunnels led to standardization of a best practice solution on FFFS in tunnels. Standardization of similar solutions to similar problems is generally desirable. FFFS is a common safety system in buildings, but there is lack of experience in tunnels, which is a key element for not using FFFS in Norway or similar countries. Investing research efforts into developing a standardized tunnel solution improves the probability of getting effective and cost-effective FFFS solutions in real tunnels. Standardization also reduces the risk associated with decision making in engineering processes and compensates for lack of engineering models and competency to dimension such systems based on scientific principles.

Whether it is FFFS, the size and shape of emergency exits, or the user-interface design of emergency control cabinets, standardization of micro-means certainly has a role to play in the future of TFSM. It is not the intention of this paper to advocate for FFFS or any other safety systems in tunnels, but to illustrate that micro-means regulations tend to work against systems-oriented thinking and innovative solutions. A regulation that has a stronger foundation in performance-based (micro-goals) and management-based (macro-means) principles, would better support a balanced selection of safety systems based on a systems-theoretical engineering approach. Macro-means ensure holistic perspectives, which should be seen as a foundation for systems thinking. Standardized solutions, based on experience and research, are important carriers of knowledge, but not as rigid requirements in regulations. A dynamic society calls for dynamic engineering practice, which involves development of appropriate regulations, TFSM principles, analysis techniques and models, and continuing professional development of tunnel safety engineers. The design of new tunnels could adhere to systems thinking principles if regulation allows some flexibility and the tunnel owner and tunnel designers embrace it at work and decision meetings.

6. Suggestions for developments towards systems-oriented TFSM

A systems perspective highlights both the design and the operation phase, where the tunnel should be kept within its safety constraints. TFSM becomes a matter of imposing effective and continuous control on important processes in real tunnels, rather than compliance with regulations. In so doing, one needs to identify the controllers and provide them with the opportunity to influence processes, identify and understand important safety critical processes, develop effective safety constraints, and make sure the controllers are updated on the status of ongoing safety-critical processes. In the design phase, scenarios play an important role in understanding the future behavior of the tunnel system. In the operating phase the key is to be aware of the status and continuously manage ongoing critical safety processes.

6.1. Improve overall processes and fire safety integration

In the following section, attention is given to the different phases of tunnel planning, design, and operation. This section takes a closer look at how fire safety, or the fire safety engineer, can be integrated in these phases. It is argued that fire safety engineers should be included (either employed by the tunnel owner or hired as a consultant) early in the planning process when important decisions are made, rather than solving problems at the end of the design. From the conception stage, where discussions about whether and where tunnels should be built, a systems perspective is relevant. Important decisions regarding, e.g., FFFS, single/twin tube design must be made early since they affect many other design parameters. For instance, some countries are very good at utilizing a parallel tunnel tube (that from a fire safety perspective eases evacuation and rescue service intervention) for other purposes, e.g., a bus lane and/or walking/cycle path. Such decisions must be made early and include fire safety as well as other concerns, otherwise they are merely a cost (a parallel tunnel only for evacuation) or utopic (e.g., a single tunnel bus lane). A good example is the new UK design guide (CD 352) that explicitly states that fire safety engineers should be involved at the outset. However, the FSE profession also needs to be viewed as a profession adding value, e.g., solving design problems, so that other stakeholders perceive that a better product or operating system is achieved.

During the design phase the tunnel owner has the possibility to communicate and develop the design based on systems thinking ideas. Then contractors, where the fire safety engineer may be one part of a larger design team, also need to adopt system thinking and demonstrate for the tunnel owner that overall system goals and functions are verified and validated. The fire safety engineer also needs to collaborate with other design branches so that all fire safety relevant interactions are considered.

Since the lifetime of a tunnel can exceed 100 years, systems thinking is required to retrofit tunnels several times in their lifetime. During such long time periods, many pre-accepted solutions can be expected to become obsolete – a dynamic mindset is required based on an appreciation of the overall tunnel system safety health. In Table 1 the overall process for the tunnel owner and fire safety engineer during planning, design and operation is summarized from a systems thinking perspective.

6.2. Re-frame the tunnel system and engineering problem

TFSM includes defining the tunnel system and its boundaries to environmental elements. How the system is defined and how problems are framed determines what is part of the design task and what constitutes boundary conditions for the design. A systems safety approach considers a broader safety domain than contemporary approaches - designing the whole of the tunnel system to avoid conditions that could lead to serious accidents. This includes for instance tunnel layout, cross-section, vehicles, users, lighting, signals, speed limits, and emergency responders.

A critical part of this re-framing concerns identifying the stakeholders and to truly understand who the key decision-makers are, at each step in the life cycle of a tunnel. The fire safety engineer needs to understand and respond to stakeholder needs regarding the fire safety design. In systems thinking the critical decision-making should be at the systems level, with input from all. This may require different decision frameworks than fire safety engineers typically use. The fire safety engineer would be involved in understanding stakeholder needs from the beginning and aiming to prevent fires, not just designing for a specific fire.

Fire safety engineers have often been trained to possess a particular view on fire safety analysis and design, including scenario development, fire quantification, design mitigation strategies, and evaluation of mitigation measures. In a more holistic systems-oriented approach, scenarios may be different (e.g., avoid accidents rather than estimate fire impacts), the types of mitigation may be different (e.g., non-fire systems for safety management), and operational issues may drive different options. The fire safety engineer often focuses on analyses to estimate what fire sizes could occur, rather than thinking about what fire size should be avoided, which aligns with stakeholder goals, e.g., more in line with Vision Zero. The fire safety engineer needs to be able to work within such a paradigm as part of a broader team. This requires that broader FSE programs are developed and offered, which is discussed in the following section.

6.3. Develop broader FSE education programs

It is not enough to put the fire safety engineer into a design team with systems thinking competence, the fire safety engineer needs to be capable of interacting and understanding the concepts and framework of systems thinking to have appropriate interactions. On one hand, the fire safety engineer needs more tunnel fire safety knowledge, and on the other hand the fire safety engineer also needs systems thinking competence. A transition to a systems thinking approach requires a different perspective from the fire safety engineers. For instance, in typical scenario-based risk analysis the hazards of different scenarios are studied, and barriers are established, while in a systems approach the constraints and processes needed to achieve safety are studied, which are two different things.

FSE competence should be generally agreed upon and defined. FSE programs need to emphasize that buildings or tunnels will always be part of a broader system. Programs need to be broadened to include infrastructure, more systems thinking, STS interactions, risk concepts and holistic design. Further, programs need to teach more about the interactions between humans, technology, organizations, and society. Stavanger university has started a pilot program that puts tunnels into a broad societal safety perspective, including traffic safety, innovation, exercises, and training. It is important to consider the context in which

Table 1
Systems thinking and fire safety integration into planning, design, and operation.

	Planning	Design	Operation
Tunnel owner	During planning systems engineering can focus on identifying stakeholders and specifying overall tunnel goals and required functions to achieve these goals.	A systems thinking work approach is needed between the tunnel owner (client) and the design team (contractors) to verify and validate that system goals and functions are achieved and implemented.	Systems thinking to ensure goals and functions are maintained and for understanding when a tunnel retrofit is needed, depending on societal changes.
Fire safety engineer	FSE competence required from early planning when key decisions regarding tunnel layout and safety are made.	Fire safety engineers need to collaborate with other design branches so that system dependencies are captured, and overall system goals are achieved.	Fire safety engineers will be needed to assess retrofitting need and alternatives.

safety assessments are conducted. As mentioned above, the fire safety engineer should have a more integrated role, e.g., more like an architect, who is responsible for fundamental qualities of an artefact from the user's perspective. A holistic perspective where the fire safety engineer is involved from the beginning until the end is suggested. FSE today may be too narrow, but a discipline working on societal safety (including fire safety and systems thinking) along the development of critical infrastructure should be involved.

6.4. *Increase the total competence of fire safety engineer*

Cooperation with the entire tunnel industry is important, which includes academia, authorities, rescue services, major tunnel users such as transport companies, tunnel owners, consultancies, and developers of fire safety systems. This process has started in Norway, and it is perceived to be very fruitful. Once this cooperation is established it is easier to include a systems thinking perspective, possibly initiated by academia.

There should be a framework for continuous professional development (CPD) that clearly shows the requirements for professional development and how much is required. A systems thinking perspective could be required in CPD. This would be a new way of thinking, perhaps, with a competency framework more focused on holistic design and STS thinking than traditional FSE fundamentals. For the CPD to work, there must also be relevant CPD activities that professionals can attend.

In theory, the profession itself should create formal mechanisms, a framework that defines patterns that each professional should follow. In the US and UK there are frameworks for CPD where each professional is required to attend courses or conferences, e.g., approved by the institution of fire engineers in the UK, which give a certain number of points. Sweden and Norway do not have any formal CPD frameworks, nor any formal qualification requirements for conducting risk assessments and preparedness analyses for (road) tunnels. However, across all countries, there are networking activities among fire safety engineers where they can share experiences and discuss common problems, such as SFPE in the USA[3] and Europe (e.g., 'BIV' in Sweden). However, given the complexity of this problem, the expectation that people will acquire the necessary competency through a personal approach to conference attendance and CPD gives no guarantee of competency. There is a certain rigidity to the profession as defined which means that the professional will follow a certain pattern. The profession is influenced by other professions and should interact and be influenced by other professions, but it is really the FSE profession that must take charge of its competence development, it cannot be done by comparison with other professions. In the oil and gas sector, there are very different approaches, where updating of professional knowledge is developed through many interdisciplinary projects, driven by well-identified corporate needs. These industries have different drivers which are important; the building industry is regulation-driven, while the oil and gas industry is more safety-driven.

[3] SFPE Europe is also increasingly influential in Europe.

6.5. *Integrate with the design team*

The search for requirements for the collective competence of the design team, in which fire safety engineering is one of many professional disciplines, builds on the assumption that the design team members need to match each other's competence to communicate and collaborate properly.

There are various disciplines in all projects. The design team is typically competent when they work well together to create a good design. This may not mean a good STS - that depends on non-design team interactions. Systems thinking competence is generally lacking. Rescue services, for instance, often bring good and different knowledge into the team.

It is argued that better integration is required within the design team, it should not consist of siloed disciplines. The design team needs to take a holistic, systems approach. This might require new courses for all disciplines and new structures for holistic decision-making. Each discipline needs a definition and relevant interactions with the other disciplines. The fire safety engineer needs to understand other competencies in the design team, such as systems thinking. For the same reason, an awareness of fire safety should be incorporated into all other professions within the design team.

6.6. *Adapting safety analysis*

As mentioned above, a systems-oriented perspective assumes that fire safety is a control problem. This suggests that one needs to adopt analytical methods that support identification and maintenance of control functions as part of the toolbox for TFSM. An example of a relevant method is Systems Theoretic Process Analysis (STPA) [66]. STPA is, according to the developers, a worst case-oriented method that, during design development, proactively focuses on how one might fail to impose control actions on the system, to prevent lack of control, and ultimately *losses,* in real operation.

STPA is initiated by considering the losses that are interesting to prevent. Such losses might be stated in the regulations, such as major losses resulting from "critical events" targeted in Directive 2004/54/EC, and also by tunnel owners in specific projects. Examples are loss of lives and health, transport flow, economic values, environmental values, etc. Building on the specified losses, the analyst identifies system-level hazards and the associated safety constraints that need to be maintained to avoid the system-level hazards. The safety constraints are effectively maintained by the actions of the system's controllers. This triggers a process of identifying the controllers and where they are in the system hierarchy. It is beyond the scope of this article to provide a full description of STPA, but a short example is provided to clarify these points. The example looks at the situation of fire in a tunnel, and includes the losses, *L1: Loss of life or injury to people*, and *L2: Loss of transport flow through tunnel*. Associated hazards and safety constraints are illustrated in Table 2, as well as *possible* control actions.

Actual control actions would be dependent on how the system is defined. In this case the analysis is not restricted to how existing tunnel systems are structured but infer control actions based on the identified safety constraints. The STPA technique is interesting in this context as it works top-down from the losses that we want to avoid to the specific

Table 2
Illustration of hazards, safety constraints and possible control actions.

Hazards, H#	Safety constraints, SC#	Possible control actions, R#
H1: Vehicle collision inside the tunnel [L1, L2].	SC1: Vehicles must satisfy minimum separation distances to obstacles and other vehicles during normal operation.	R1: Driver hits brake when separation distance violates minimum requirements. R2: Sensor system in tunnel alerts drivers about violation of minimum separation distance in normal operation and standstill situations. R3: External controller notifies driver about a violation of minimum requirements.
	SC2: If H1 occurs, the collision must be detected, and measures taken to prevent fire and notify tunnel users.	R4: Tunnel user initiates measures to prevent fire. R5: Sensor in vehicle and/or tunnel detects collision and informs external tunnel operator through a communication system. R6: External tunnel operator initiates measures to prevent fire.
H2: Vehicle catches fire and emits toxic smoke and heat into the tunnel [L1, L2].	SC3: All vehicles in the tunnel must be approved in roadworthiness inspections every 24 month.	R7: Road authorities keep a national register of approved vehicles. R8: Police stop unauthorized vehicles from entering tunnel (random sample controls). R9: Sensor in tunnel alerts external tunnel operator about unauthorized vehicle through a communication system.
	SC4: If H2 occurs, the fire must be detected, and measures taken to protect people from smoke and heat.	R10: Sensor in vehicle or tunnel detects fire and notifies external tunnel operator through a communication system. R11: External tunnel operator closes tunnel and informs tunnel users about appropriate actions.
H3: Fire spreads from initial vehicle to adjacent vehicles [L1, L2].	SC5: Vehicles must satisfy minimum separation distances to other vehicles at standstill situations.	R12: National Road Authorities develop minimum requirements for separation distance at standstill. R13: Driving schools include training on separation distance in tunnels. R2 is relevant to maintain SC5 as well.
	SC6: Equipment to prevent fire development and fire spread must be available in the tunnel.	R14: Tunnel owner installs and maintains appropriate manual firefighting equipment in the tunnel. R15: Tunnel owner installs and maintains an appropriate FFFS in the tunnel.
H4: Tunnel users are unaware of appropriate actions in in case of fire in the specific tunnel [L1].	SC7: In case of fire, tunnel users must receive enough information to facilitate a self-rescue process in the specific tunnel.	R16: All drivers of HGVs are trained to initiate and lead self-rescue processes. R17: Tunnel owner installs and maintains information about the self-rescue process in the specific tunnel by emergency stations. R18: Tunnel owner installs and maintains a system to facilitate communication between tunnel control center and tunnel users. R19: External tunnel operator informs tunnel users about appropriate actions to facilitate self-rescue in case of fire.

control actions we need to impose on the system to maintain safety. It also facilitates a discussion and analysis of the "tunnel system". Analyses are not mainly conducted to prove that a design is safe, but to support the design of control structures that will produce safety over time. This is important, because it shows that safety management is a matter of continuous work in collaboration amongst actors on several layers of the system hierarchy.

Examination of catastrophic events frequently demonstrates that the proximate cause of an event is not the root cause (see e.g. [17,18,22,67]). Rather, a disaster is better understood as a system migration towards a hazardous state, involving latent organizational factors working to escalate the development of an event and reduce the efficiency of the emergency response. A systemic approach calls for active safety management and a strong safety culture within the system's organizations. Principles of high reliability organizations are inspirational [68,69], these principles include preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience and deference to expertise.

7. Concluding remarks on future approaches to TFSM

Tunnels are unique and complex systems that require an enormous amount of time and resources in planning, design, and operation. Most tunnel fire safety designs optimize system by system without consideration of how these systems are interconnected and affect the overall tunnel system from a systems perspective. Fire safety issues are treated in an isolated way, which is insufficient. In this paper we have investigated regulatory design and engineering practice in five countries with the assumption that systems thinking could support existing principles based on experience and risk management, cf. Fig. 1. System ideas are introduced through fundamental goals and visions, such as Vision Zero in Sweden and Norway and the Safe System approach in Australia. Systems thinking principles have been prevalent in European countries since the introduction of Directive 2004/54/EC. Still, the overarching principles have yet to trickle down to engineering practice and education.

The analysis presented here challenges existing tunnel safety regulations in two aspects: 1) the design of tunnel safety regulations is not optimal with regards to promoting systems thinking in TFSM, and 2) there is a connection between existing regulations, engineering practice and education. To improve the situation, tunnel safety regulations could be re-designed to strengthen fire safety engineer's ability to work on a design team using systems thinking principles. The first issue involves designing tunnel safety regulations around macro-means-oriented principles, while keeping an appropriate balance with micro-goals and micro-means principles. The second issue is closely connected with the formal competence and experience that engineering practitioners are expected to represent. At the core of the problem is the qualifications of FSE/FSM programs and CPD that are lacking from a tunnel and systems thinking perspective.

Fire safe tunnels can only be achieved by competent professionals and reflective users. So the responsibility of delivering a fire safe tunnel is that of the professionals involved in the planning, design, and operational phase, considering the user's constraints. Other professions should understand that fire safety issues should be included early in the planning and design process and fire safety engineers are necessary to solve important tunnel problems, e.g., single or twin tube tunnel. A systems perspective in which the whole tunnel construct is viewed and conceptualized as a 'system', from conceptualization to operations, would be beneficial for better overall decision-making. The role of the FSE would change from 'specifier of fire protection systems' to more integrated 'problem solver' as part of the design team. Such a perspective would emphasize:

- Multi-stakeholder system objectives and involvement.
- Dependencies and interactions between different components.
- Multi-competence involvement.
- Flexibility for adjustments.
- Inherently safer and fail-safe design.
- Systems focus (the whole before the subsystem).

Author statement

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Declaration of competing interest

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Data availability

Data will be made available on request.

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