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Emergency preparedness for tunnel fires – A systems-oriented approach

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ABSTRACT

Efficient emergency response is key to preventing major losses in tunnel fires. Our general concern in this paper is the degree to which tunnel systems are prepared and the means by which we can be prepared for a major fire in a single-tube road tunnel. Conformance to prescriptive regulations dominates existing practice in the area of emergency preparedness. Risk-based approaches exist but have little influence on emergency preparedness designs for tunnel systems. A successful emergency response to tunnel fires is dependent on many actors collaborating under serious time constraints. Safety becomes a matter of controlling critical processes necessary to keep the system in a safe state. Efficient decision-making in situations of major uncertainty is vital, to achieve safety goals. This essentially means that efficient emergency preparedness for road tunnels is a matter that needs attention in the early design phases and continuous improvements during the operational phase. To achieve high-performance emergency preparedness against tunnel fires, there is a need for radical changes to the design and operation of tunnels. In this paper, it is claimed that a system-theoretic approach is appropriate to deal with the tunnel system's complexity and to drive the design of appropriate control structures for critical processes, from the design phase to the actual emergency. It is shown how system theoretic approaches will change the safety management practices for tunnels and how this will increase consistency between potential fire scenarios and associated control actions.

1. Introduction

1.1. Tunnel developments

Let us start with a scenario: Consider you are driving into a dark hole in the mountain: the sudden change from day to night and the fumbling to get the headlights on. Water is dripping on your windshield, and the rough-surfaced walls are passing by at 80 km/h. At regular intervals, you pass emergency stations. Small signs indicate that there is a telephone and a fire extinguisher there. In an emergency, using this phone will put you in direct contact with the traffic control center (TCC) and immediately confirm your position in the tunnel. This is useful for the TCC and the emergency responders. You, on the other hand, try to master the balancing act of avoiding traffic coming in the opposite direction and hitting the tunnel wall. Maybe you notice the signs and spend time reflecting on their meaning, or maybe not.

Not many years ago, many transport tunnels were merely holes through the mountain: simple constructions to enable roads and railways to pass through otherwise impassable terrains. While this description is still true for many Norwegian tunnels, regulatory and technological developments over the past two decades have led to major changes. Generally, modern tunnels are less hostile environments than their predecessors were. For example, the portals of road tunnels are equipped with railings and a more crash-friendly design. Better lighting technology reduces the rapid transition of light from the outside to the inside. Tunnel owners invest more in designing better banquettes and guiding edges, to reduce the hazard of running off the road. Traffic management equipment, such as camera surveillance (ITV) and automatic incident detection (AID), have become mandatory in more tunnels. The same goes for emergency response systems such as emergency lighting, variable signs for notifications, constantly illuminated and better protected emergency stations, and even loudspeakers for communicating with drivers.

Looking ahead, the tunnel safety industry is considering even more safety measures. How can tunnel owners make use of new communication technology, the Internet of things, artificial intelligence or

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machine learning? Would it be possible in the future to keep track of every vehicle and person in every tunnel, providing them with precise instructions during an emergency? The opportunities are many: cheap Bluetooth beacons, detection of humans by exploiting existing fiber cables, vehicle-to-vehicle communication or drones performing continuous inspections in the tunnels. Maybe it will also become possible to build safe evacuation rooms in long single-tube tunnels, where traffic load is limited and no other means of egress exist.

1.2. Tunnels, fire risk and emergency response

Societal pressure to increase safety and emergency preparedness in tunnels is strong. The tragic fires in central Europe around the turn of the millennium, which so clearly illustrate the major consequence potential of serious events in general, and fires in particular, is a reminder of why. There are over 20 fires in Norway's 1150 road tunnels each year (Nævestad & Meyer, 2014), some of them quite serious e.g. Oslofjord 2011 (NSIA, 2013) and 2017 (NSIA, 2018), Gudvanga 2013 (NSIA, 2015) and 2015 (NSIA, 2016a), Skatestraum 2015 (NSIA, 2016b) and Fjærland 2017 (NSIA, 2019). Investigations by the Norwegian Safety Investigation Authority (NSIA) have raised concerns regarding the risk management approaches (NSIA, 2013), and the emergency preparedness systems have also been criticized (NSIA, 2015; 2016a).

The European Commission's Directive on minimum safety requirements for tunnels in the Trans-European Road Network (EU, 2004) was a result of the European fires around year 2000. Many Norwegian tunnels (173 tunnels) fall under the scope of the Directive. The European Free Trade Association's (EFTA) Surveillance Authority (ESA) recently concluded that *"Norway has failed to fulfil its obligations under Article 3(1) and 11 of the Directive"* (ESA, 2020), with 64 tunnels not in compliance with the Directive over one year after the April 30, 2019 deadline. A hint of this conclusion came in 2016, when the Office of the Auditor General of Norway (OAGN) issued a report on safety management in road tunnels. The report points at several challenges, such as: failure to include tunnel-specific issues in risk assessments; lack of fire drills in several tunnels; lack of documentation of safety management procedures; lack of information to drivers about safe behavior in tunnels; and weak management and monitoring by the central authorities (OAGN, 2016).

Transport tunnels are slowly developing into high technology systems. Many would argue that the level of safety is increasing, and maybe it is. Nevertheless, introducing new technology, coupling more systems and exploiting new opportunities in existing systems lead to a new level of complexity. Expanding the perspective, we must also consider trends of traffic growth, climate change and increased dependence on national critical infrastructures. Transportation infrastructures are generally vulnerable, due to lack of redundancy, long repair time, rerouting difficulties or cascading failures and interdependencies (Pitilakis et al., 2016). Their damage could be greatly disruptive in terms of safety of life, business disruption, access to emergency services and key lifeline utilities, rescue operations and socioeconomic impacts. The potential to achieve major safety improvements exists. In the process of exploiting opportunities, it is essential to avoid creating new, hidden vulnerabilities that reveal themselves when exposed to accidental loads. This is where good emergency preparedness planning comes in.

1.3. Good emergency preparedness and safety

Emergency preparedness involves all technical, operational and organizational measures that prevent a dangerous situation that has occurred from developing into an accidental event, or which prevent or reduce the harmful effects of accidental events that have occurred (Njå, 1998; Njå et al., 2020).

A literature search, using the search engine, Scopus, on the keywords "tunnel risk", "tunnel emergency", "tunnel preparedness" and "tunnel system safety" led to a selection of 48 initially interesting articles. Browsing through the articles' abstracts led to the definition of nine classes of topics. Table 1 shows the distribution of articles over the nine topics. It is interesting to notice that the number of articles in classes 1, 4, 6 and 7 totals 25. A possible interpretation is that *tunnel risk, emergency and preparedness* are currently closely associated with regulative requirements and specific safety measures, fire and smoke transport, previous events (statistics) and evacuation issues. The number of articles in class 1 could also be the result of the traditional safety management strategy in the European transport sector, i.e., conformance to prescriptive regulations (Marsden & Bonsall, 2006; Ingason & Wickström, 2006; Bjelland & Aven, 2013; Kazaras & Kirytopoulos, 2014).

In this paper, we are interested in approaching tunnel emergency preparedness from a holistic and alternative perspective. All articles classified as topic 2 are part of understanding the state of the art. We also prioritized analyzing a selection of articles classified as topics 1, 3 and 9.

Several authors emphasize performance-based targets and leading performance indicators as important for safety development in the transport and tunneling industry (see e.g. Marsden & Bonsall, 2006; Ingason & Wickström, 2006; Gehandler et al., 2014; Kazaras et al., 2014; Pitilakis et al., 2016). According to Marsden & Bonsall (2006), defining performance targets enables better public management, legal and contractual obligations, resource constraints, consumer orientation and political aspirations. Gehandler et al. (2014) outline a framework built on five *main functional requirements* for fire safety in tunnels: 1) organization and management, 2) limiting the generation and spread of fire and smoke, 3) providing the means for safe self-evacuation, 4) providing the means and safety for the rescue service to intervene, and 5) ensuring the load-bearing capacity of the construction.

Kirytopoulos and coworkers (Kazaras et al., 2012; Kazaras & Kirytopoulos, 2014; Ntzeremes & Kirytopoulos, 2018; Ntzeremes & Kirytopoulos, 2019) have made a noticeable contribution to tunnel safety research, from a risk assessment and systems thinking perspective. The authors are critical of quantitative risk assessments (QRA), based on their limited ability to take into account human factors in emergency situations, organizational aspects, software behavior, system complexity and the dynamic nature of risk. The lack of appropriate data and the treatment of uncertainties are also issues. The authors propose systems theory as a basis for an alternative approach, based on Leveson's STAMP model (Kazaras et al., 2012). The STAMP model should complement QRA approaches, not be a substitute for them.

Alvear et al. (2013) present a decision support system for emergency management in tunnels. Their idea is to provide operators with decision recommendations using predictive tools to deal with emergencies in real time. They argue that tunnel safety is dependent on three major factors: *1) tunnel design, 2) tunnel management,* and *3) emergency response*. Current approaches focus on tunnel design and facilities, risk analysis and contingency plans, implying a lack of focus on 2) and 3). The tunnel operator plays a critical role in initiating the emergency response,

Table 1
Classification of literature: distribution of articles over nine classes of topics.

Topic ID	Topic	Articles
1	Regulations, design, technical requirements and specific safety measures	12
2	Alternative approaches to safety and emergency management in tunnels	8
3	"Traditional" risk and hazard assessment models (normative or case studies)	6
4	Smoke transport (CFD, experiments, etc.)	5
5	Emergency management: frameworks, models and simulators	4
6	Accident investigation and fire statistics	4
7	Evacuation from tunnels	4
8	Review papers on traffic safety design and fire safety design of tunnels	3
9	Other	2
	SUM =	48

informing tunnel users and emergency services. Fixed protocols are often the basis for the operator's decision-making, while the emergency is inherently dynamic and calls for a flexible decision-making process.

Fridolf et al. (2013) argue that evacuation theory from building research is generally applicable to tunnels, although some differences exist. The *behavior sequence model*, the *role-rule model*, the *affiliative model* and *social influence* are explanation models for evacuation behavior. A major difference between buildings and tunnel systems is often the longer distances to emergency exits or safety shelters. This calls for measures to increase walking speed. It also inhibits emergency personnel and makes rescue operations more complex. Trains and cars may also function as obstructions that affect the flow of people towards the emergency exit. Information given during an emergency must be *clear and coherent*. Tunnel design does not pay adequate attention to people with disabilities. Tunnel users with disabilities, e.g., wheelchair users, must rely on assistance from other tunnel users.

1.4. Motivation and problem formulation

Investigations after major accidents and system audits have revealed severe shortcomings in the safety management of tunnels (NSIA 2013; NSIA, 2018; Njå et al. 2013; OAGN 2016). Real-time understanding of risk in the tunnel systems is lacking. With hindsight, we were able to acknowledge that the level of risk in the Oslofjord tunnel was unacceptable before the major fire in 2011. With hindsight, we can question the smoke management strategy adopted in both the Oslofjord and the Gudvanga fires in 2011 and 2013 (NSIA, 2013; 2015), respectively. With hindsight, we acknowledge that the emergency response systems could have a better design, coordination and training. New tunnel systems need new approaches for emergency preparedness planning.

Emergency preparedness needs attention in the early design phases and continual improvements during operation. If our existing approaches to safety management are not up to this task, which seems to be the case, we need to conscientiously search for improvements. An approach based on systems theory is promising. First, systems theory aims at achieving a holistic understanding of systems, which means that understanding the increasing complexity of tunnel systems is a major goal of the process. Existing approaches come with few incentives to explore and understand complexity, and over-simplifications and a rejection of uncertainties often result. Second, systems theory acknowledges the dynamic nature of complex and open socio-technical systems. Existing approaches are more adapted to compliance and verification than to understanding and providing a foundation for managing safety, from a lifetime perspective.

In this paper, the framework from Bjelland et al. (2015) is adopted for designing emergency preparedness and response measures in an assessment of control structures responding to fire risks in a single-tube road tunnel. Our study takes a Norwegian perspective concerning road tunnel standards, safety regulations, dimensioning of emergency response and its organization, climate and other frame conditions. Our major concern in this paper is to contribute to a framework for understanding and developing safety constraints for road tunnels. Safety constraints are a central concept to systems theory, and it is critical that a sound understanding underlies design processes and tunnel operation.

2. Existing practice for design and operation of tunnels

2.1. Existing safety regulations

There are several ways to design safety regulations, all with their own benefits and challenges. Table 2 is a presentation of a possible classification scheme consisting of two axes. On the one axis, the framework distinguishes between regulating means or ends (outcomes). On the other axis, the framework distinguishes between regulating the components of a system (micro level) or the system as a whole (macro level) (TRB, 2017; Lindøe m.fl, 2018). Regulating the means implies presenting more or less detailed expectations on design, procedures or actions to be taken. This is in contrast with regulating the ends, where the performance and ultimate outcomes of the system are to be evaluated. The traditional inspection function (either internal or external) is set up to control immediate adherence to norms, rather than evaluating the performance of a given system. When controlling performance, it is often necessary to penetrate the given system in more detail when trying to judge whether the system established is designed to deliver outcomes as regulations require. Effective controlling of the ends is often regarded as dependent on a high level of trust among the actors in the system (Hellebust & Braut, 2012).

Table 2
Classification scheme for regulation designs (TRB, 2017).

	Means	Ends
Micro	*Micro-means*"Prescriptive"	*Micro-ends*"Performance-based"
Macro	*Macro-means*"Management based"	*Macro-ends*"General duty/liability"

The Road Tunnel Safety Regulations (SD, 2007) (includes the EU Directive) and the "N500 Road Tunnels regulation" (NPRA, 2020) generally fall under the category *micro-means*. Compliance with detailed safety measures generally implies an acceptable safety level. However, the regulations also include requirements to conduct risk analyses, *macro-means*, for most tunnels (NPRA, 2020). Article 11(1) of the Road Tunnel Safety Regulations allows for derogations for innovative techniques. Provided the alternative safety measures will result in equivalent or improved protection, the administrative authority may grant such derogations (EU, 2004).

In practice, it is cumbersome to derogate the regulations in design processes. This involves preparing an application based on a risk analysis, both when adding and removing safety measures. The Norwegian Public Road Administration (NPRA) is also restrictive in its policy to approve added safety measures, as this could lead to precedence in similar cases and higher overall costs of tunnel construction. Hence, the regulations and the administrative management of the process provide few incentives for risk-based safety engineering. Risk analysis becomes a tool to verify compliance with the regulations, rather than a tool to explore the risks of the specific tunnels and an important foundation for design and emergency preparedness decisions.

In November 2016, the NPRA issued a new version of *Handbook N500 Road Tunnels* (NPRA, 2016). This version introduces the concept of emergency preparedness as a part of the safety management of Norwegian road tunnels. An emergency preparedness analysis is now required for tunnels greater than 1,000 meters. The emergency preparedness analysis must cover the phases from alert, mobilization, rescue, and evacuation to normalization. There is, however, no mention of the important phases of detection and combat, which are natural parts of an emergency preparedness analysis (Njå, 1998).

Although road tunnels are required to be designed based on risk assessments and emergency preparedness analyses, a major problem is that no one has described acceptable risk levels or specific requirements for emergency preparedness. As a quality assurance measure, N500 requires the Norwegian Public Roads Directorate to approve the method chosen for risk and emergency preparedness analyses. This practice may prevent sub-quality analyses. However, as the selection of methods for risk and preparedness analyses depends upon the scope of the analyses and available data, the practice imposes major competency requirements on those who shall approve the methodological design.

2.2. Vertical (silo) thinking

Vertical thinking, which dominates current design and emergency preparedness practices, is about building layers on layers of knowledge within a certain field, without looking at what goes on outside your "silo of knowledge". This way of thinking may impose serious restrictions on the understanding of relevant knowledge for a specific field of engineering, such as safety engineering.

The cost of silo thinking may be a lack of attention to knowledge outside the silo, which may lead into an intelligence trap. Among other things, the intelligence trap is characterized by defending a bad solution through the application of seemingly flawless logic. An example of such thinking in the tunnel safety industry is the major drive to develop standardized risk assessment models. In Norway, examples are *"TUSI"* (NPRA 2007) and "TRANSIT" (Schubert et al., 2011). Recently, a new risk model from the Norwegian Institute of Transport Economics (ITE) has replaced TUSI's fire model (Høye et al., 2019). Different actors all over Europe are taking part in filling the silo with risk analysis models (PIARC, 2008). Given that the European Commission is asking for harmonized risk analysis approaches (EU, 2004), such developments are understandable (Kazaras & Kirytopoulos, 2014).

However, there is nothing wrong with filling the silo with knowledge and better models. The real danger concerns understanding these models as the truth about safety, not looking beyond their limitations and simplifications. Lateral or multidisciplinary thinking is a preventive measure in this respect. Lateral thinking involves expanding the repertoire of patterns through which we think about the world (ASCE, 2008:52; Blockley & Godfrey, 2000:119; de Bono, 1990). This is important, in order to obtain holistic understanding of emergency preparedness for complex tunnel systems. Developing design and emergency preparedness approaches based on systems theory will prevent safety from being an issue treated in isolation.

3. Foundation for dimensioning events – Materials and methods

This section includes findings from investigations after some major Norwegian tunnel fires during the past decade. Our starting point for the analysis is to gain understanding of the phases of emergency preparedness, i.e. detection, alert, mobilization, rescue, combat, evacuation and normalization, by using information from the events. In this paper, the safety management practices involved are studied, along with whether there are common factors that complicate the emergency response performance.

These events, and our understanding of them through investigations, are also important reminders as to which fire scenarios to expect in the future. Dimensioning scenarios are important in determining what loads a fire may impose on the emergency response system, including the tunnel's construction and its technical safety systems, the drivers and passengers and the emergency responders (fire, police ambulance, Norwegian public road administration, municipalities, hospitals and so on).

No one was killed in the presented fires, but international tunnel fires, such as the Mont Blanc (Duffé & Marec, 1999; Voeltzel & Dix, 2004), the St.Gotthard (Bettelini et al., 2003; Martin et al., 2005; Voeltzel & Dix, 2004) and the Tauern (Colombo, 2001) tunnel fires remind us of the extent and the devastating impact. However, for the Norwegian fires discussed in this study, it is easy to portray alternative circumstances that may have led to several fatalities.

3.1. *Introducing the cases*

Our analysis builds on seven fires in Norwegian road tunnels, for each of which a thorough accident investigation report by the Norwegian Safety Investigation Authority (NSIA) exists. Table 3 gives an overview of the fires, tunnels and some information about the event. A common characteristic is that all tunnels and events include single-tube tunnels with bi-directional traffic. Oslofjord and Skatestraum are subsea tunnels, while the others are mountain tunnels. All tunnels are rather narrow, having a width of about 8-8.5 meters and a height of 4.5 m, except Oslofjord which is a "T11 profile" with three driving lanes (two uphill and one downhill).

3.2. *The process of detecting events and alerting emergency responders and drivers*

The process of detecting a fire in a road tunnel is critical for initiating the relevant emergency protocols/processes. A general challenge in Norwegian road tunnels is the lack of systems for direct and specific fire detection. Not one of the tunnels mentioned in this study had specific fire detection systems. However, the Oslofjord tunnel was equipped with ITV and AID systems that detect vehicles that stop in the tunnel (NSIA 2013; NSIA 2018). The four other tunnels included in this analysis did not have ITV/AID systems. Detection of fire is generally intended to happen through drivers seeing the fire and then using the emergency telephones or fire extinguishers in the tunnel to notify TCC. When an emergency telephone is being used or a fire extinguisher is lifted from the cabinet, an alarm is issued to TCC, and the location is confirmed. A general challenge is that drivers in the tunnels do not use the emergency telephones or fire extinguishers. Instead, they use their own mobile phones, which was the case of the first notification in Gudvanga 1 (NSIA, 2015), in Gudvanga 2 (NSIA, 2016a) and in Måbø (NSIA, 2017). In Skatestraum (NSIA, 2016b) and Fjærland (NSIA, 2019), the fire was first notified by the use of tunnel equipment. Since Oslofjord had ITV/AID systems, the fires were detected by TCC before anyone in the tunnel called it in. Hence, having a system for detection makes the actions of individual drivers less critical, as it becomes possible to combine different information sources.

Table 3
Overview of tunnel fires included in this study.

Event	Vehicle*	Triggering fire cause	Tunnel length	Open since	AADT** on event (HGV)	Max gradient	Estimated peak fire effect	Ventilation dim.
Oslofjord 1, 2011	HGV	Engine failure	7.2 km	2000	7 000 (15 %)	7 %	70–90 MW	50 MW
Gudvanga 1, 2013	HGV	Engine failure (oil leak under pressure)	11.4 km	1991	2 000 (25 %)	3.5 %	25–45 MW	5 (20) MW***
Skatestraum, 2015	Petrol tanker	Collision with tunnel wall	1.9 km	2002	300 (10 %)	10 %	440 MW	N/A
Gudvanga 2, 2015	Bus	Engine failure	11.4 km	1991	2 000 (27 %)	3.5 %	30 MW	5 (20) MW***
Måbø, 2016	HGV	Hydraulic leak near exhaust system	1.9 km	1986	1 000 (N/A)	7.8 %	50 MW	N/A
Fjærland, 2017	Road sweeper	Hydraulic leak near engine	6.4 km	1986	1 500 (20 %)	3.2 %	20 MW	N/A
Oslofjord 2, 2017	HGV	Engine failure	7.2 km	2000	9 300 (15 %)	7 %	N/A	50 MW

* HGV is an abbreviation for Heavy Goods Vehicle.
** AADT is an abbreviation for Annual Average Daily Traffic.
*** The fire ventilation handles fires up to 20 MW but 5 MW is the basis for design (NSIA, 2015).

In some Norwegian regions, using the emergency telephone and fire extinguishers triggers several automatic measures, such as closing the tunnel by red blinking lights, activating fire detection in a predetermined fire mode and activating emergency lighting. This automatic programming was present in Gudvanga 1 and 2 (NSIA, 2015; NSIA, 2016a), Måbø (NSIA, 2017) and Fjærland (NSIA, 2019). In the Oslofjord tunnel, actions are taken manually be the TCC operators, based on alarms and information obtained through the ITV/AID systems (NSIA, 2013; NSIA, 2018).

The process of alerting emergency responders and drivers is dependent on well-defined protocols for interacting, available communication systems and relevant information to communicate. The Oslofjord fires stand out, since the tunnel is equipped with ITV/AID systems. This makes it possible for the TCC to gather important information that is useful for managing the event. The other tunnels in this study do not have such equipment, and the TCC and emergency responders are dependent on information from drivers or being present in the tunnel.

In the Gudvanga 1 fire, the fire was detected by a driver using a mobile phone to call the central emergency number, 110 to alert the regional fire operation center. Three minutes after being notified about the event, 110 central alerted TCC with a request to close the tunnel. The tunnel was then closed manually by activating red blinking lights. Since the fire was called in by a driver using a mobile phone, TCC did not know the location of the fire, even though a fire extinguisher was removed from a nearby cabinet five minutes after the first notification. TCC was lacking confirmation from the 110 central and thus the necessary decision support to activate “turn and drive out” signs. It was when a firefighter lifted a fire extinguisher from an emergency station near to the fire that the location was first confirmed. This happened approximately 45 minutes after the first call about the fire (NSIA, 2015). In contrast, during the Oslofjord 1 fire, the TCC knew the exact fire location immediately and had an overview of the remaining vehicles in the tunnel before it was filled with smoke. Nine minutes after the fire was detected, TCC broadcasted a radio message to all vehicles in the tunnel. This radio message was later repeated (NSIA, 2013).

The Fjærland tunnel fire is also interesting in regard to the alert phase. NSIA is concerned with the lack of appropriate communication equipment, communication protocols and briefing of the crew in this event (NSIA, 2019). The fire occurred during regular washing of the tunnel late in the evening. During the washing operation, an escort vehicle was leading convoys, to maintain traffic flow. When the driver of a sweeping vehicle discovered there was a fire in his vehicle, he retrieved a fire extinguisher from a nearby emergency station to notify TCC about the fire. He then notified the police, using his private mobile phone, and triple notification to all emergency services was issued. While talking to the police, the driver of the sweeping vehicle was unable to confirm what tunnel he was in. The driver was also unable to notify his colleagues in two washing cars ahead, as well as the escort vehicle of the convoy. The mobile phone intended for this purpose had been left behind in the vehicle when he evacuated. When TCC reached out to the contact person, who was the driver of one of the washing cars, the contact person could not confirm that there was a fire. Communication went back and forth between different actors in the washing and traffic management operation, trying to find out what was going on. The driver of the sweeping vehicle started walking towards the portal and met the convoy and escort vehicle. He notified the driver of the escort vehicle, who then notified the drivers in the convoy.

3.3. The process of mobilization, focusing on situation awareness for emergency responders

As mentioned in the previous section, systems for gaining situation awareness are not commonplace in Norwegian tunnels. In our study, only the Oslofjord tunnel had ITV/AID systems. TCC is dependent on information and actions from drivers and emergency responders, to gain awareness of the situation. Although the Oslofjord tunnel had ITV/AID systems, there was no system for automatic real-time registration of vehicles in the tunnel. The location and direction of vehicles is considered by the operators to be critical for effective traffic surveillance and management. The operators used the ITV system manually to count vehicles, which is a time-consuming task (NSIA, 2018).

It is clear that NSIA is critical of the safety management of the Oslofjord tunnel and the lack of ability to maintain a calibrated risk picture (NSIA, 2018; NSIA, 2013). After Oslofjord 2, NSIA points out that the emergency preparedness plan refers to annual average daily traffic (AADT) numbers from 2010, while the numbers in 2017 were 30 % higher. They also point out that the defined tunnel class determines maintenance intervals. The tunnel was originally defined as “class C” but should have been “class D” in 2017, according to its development in the AADT level. NSIA is also critical of the selected six-year frequency of periodical inspections, as the status of technical safety systems may affect the possibility to conductg self-evacuation during a fire event. Lacking information about existing technical faults led to unexpected workloads for the operators during the fire, which potentially diverted the focus away from gaining situational awareness. NSIA specifies a safety recommendation concerning a system registering the totality of faults, in order to conduct efficient surveillance on the tunnel’s technical safety status (NSIA, 2018). In addition, one “turn and drive out” sign was out of service, radio messaging did not work during the fire, the emergency responders’ communication system was not working properly, and TCC received a door alarm from seven evacuation rooms, but only one room was in use. In the Skatestraum fire, the TCC operator was unaware that the radio broadcasting system was not functioning during the fire (NSIA, 2016b).

3.4. The process of combating the fire, focusing on smoke control strategies

Fire ventilation becomes necessary because the fire is allowed to grow. It is interesting to note that the driver of the vehicle involved in the fire tried to extinguish the fire using portable fire extinguishers in both Oslofjord 1 and 2 and in Gudvanga 1 and 2. However, the driver was unable to extinguish the fire using the available portable equipment (NSIA 2013; 2015; 2016a; 2018).

All tunnels in this study include systems for longitudinal fire ventilation. In all cases, the ventilation direction is predefined, on the basis of the most capable fire department having access to the accident. There are, however, different strategies for activating fire ventilation. In the Oslofjord tunnel, the ventilation stops when the tunnel closes. The TCC operator uses the first (maximum) seven minutes after detecting a fire to gain an understanding of the situation. The operator shall, in collaboration with 110 central or the on-scene fire commander, decide when or if to start smoke ventilation. In Oslofjord 2, this procedure was in use, and a decision to start fire ventilation was taken six minutes after the ventilation system was shut down. Six ventilators did not work, four of which were known to be out of service before the fire. The direction of the ventilation is predefined in the protocols on the basis of fire department capacity. NSIA raises questions about this protocol, as, in both Oslofjord 1 and 2, it led to smoke filling a large portion of the tunnel, exposing more vehicles and people to smoke.

In the western region of Norway, where the Gudvanga, Fjærland and Skatestraum tunnels are located, fire ventilation starts automatically in the predetermined direction when a fire extinguisher is taken out of its cabinet or when an emergency phone is in use. In Gudvanga 2, the fire department requested TCC to wait before activating the longitudinal fire ventilation, but ventilation activated automatically towards Gudvangen when a bus driver removed a fire extinguisher from the tunnel wall. This resulted in changing the natural draft direction, which was towards the nearest portal (360 m distance to the Aurland portal) at the time of the fire. When the direction of flow was changed, smoke was pushed a distance of nearly 11.4 km. Five persons were trapped in the smoke, none of whom lost their life (NSIA, 2016a). In Gudvanga 1, a driver made use of a mobile phone to notify authorities about the fire. Therefore, TCC had to activate the fire ventilation manually. The Gudvanga 1 fire was also located closer to the Aurland portal. The predetermined direction of fire ventilation led to approximately 8.5 km of the tunnel being filled with smoke. A total of 67 people were trapped in the smoke and had to evacuate the tunnel under severe conditions. No one lost their life, but five were diagnosed with very serious injuries and 23 with serious injuries (NSIA, 2015).

According to normal procedure, fire ventilation is activated automatically when a fire extinguisher is removed from an emergency station in the Fjærland tunnel. However, TCC stopped the fire ventilation manually, assuming the sweeping vehicle had damaged an emergency station. Seven minutes later, the fire was confirmed at TCC and fire ventilation was activated manually (NSIA, 2019). This illustrates the importance of situation awareness and confirmation of the event.

3.5. The process of evacuation and rescue

Challenges associated with the evacuation process and people getting trapped by the smoke were major issues in both Oslofjord 1 and 2 and Gudvanga 1 and 2, and also in Fjærland. A common factor in these fires is smoke being ventilated towards the portal furthest away from the fire, the direction having the greatest potential for people being trapped. A major difference, however, is the lack of measures to obtain situational awareness in the two tunnels. The Gudvanga tunnel did not have any cameras installed, while cameras were available in both Oslofjord fires.

In accordance with the emergency preparedness plan for the Gudvanga tunnel, longitudinal fire ventilation was activated in the predetermined direction, in Gudvanga 1. The decision to activate fire ventilation, and its direction, is automated, without any concern for the specific situation. It is possible to override the ventilation strategy, i.e., stop, decrease or revert the flow (NSIA, 2015). However, building a solid decision support for making this choice is difficult, time-consuming and highly dependent on information from people inside the tunnel. In Gudvanga 2, five persons were trapped in the smoke and sought refuge in vehicles. After receiving information about trapped people (contact via mobile phones), the emergency responders ordered a change in the ventilation direction. The five people in the tunnel were found by smoke divers from the fire department after ca. 1.5 hours and were transported to hospital for treatment for smoke injuries (NSIA, 2016a).

The possibility for gaining situational awareness to support the evacuation process was better in the Oslofjord fires. The exact location of the fire was known as soon as the HGV stopped. The operators at TCC were also able to perform a manual search of the tunnel using the ITV system, before activating the fire ventilation system. The support for optimizing the ventilation strategy, to support the evacuation process, was thus much better. Still, in Oslofjord 1, a decision was taken to ventilate the tunnel in the predefined direction, and 5.5 km of the tunnel was filled with smoke. When the fire started, 34 persons were in the tunnel. Of those, 25 managed to evacuate without assistance; emergency personnel assisted nine people, eight of whom had sought refuge in SOS stations and later managed to enter the space between the concrete tunnel lining and the rock. Thirty-two people were treated in hospital (NSIA, 2013). After Oslofjord 1, the NPRA installed evacuation rooms in the tunnel. In Oslofjord 2, two people evacuated to evacuation rooms and were there for 32 and 42 minutes before being assisted by the fire department. Through cameras and telephones in the evacuation room, operators from the TCC were able to stay in continuous contact with the two people during the event (NSIA, 2018).

The Skatestraum fire was an extreme event. Calculations show that the heat release rate may have been above 400 MW during the initial phase of the fire, and the ceiling temperature above the fire was calculated to be about 1350 °C (NSIA, 2016b). In situations like these, instant decision-making and actions are necessary to save lives. The Skatestraum fire may serve as an example that an effective evacuation process is possible when the risk awareness of the involved personnel matches the situation.

In summary, also discussed by (Njå & Kuran, 2015), it takes too long before road users are aware of dangerous situations in tunnels and prepare for self-evacuation. The organizing of self-evacuation is arbitrary and, to a very small extent, adapted for road users' needs. The road users do not possess knowledge of tunnel fires, e.g., illustrated by keeping little distance from the vehicle in front and postponing evacuation actions. From a system's perspective, buyers of transport services, transport salesmen, forwarding agents, transport companies and drivers of HGVs containing a large amount of energy have been considered and scrutinized very little, with respect to their roles and responsibilities regarding major fires in tunnels. Knowledge amongst tunnel authorities, owners and users regarding fire dynamics, heat development and smoke dispersion in tunnels is weak.

4. Systems thinking in safety management – A matter of control

4.1. Introducing systems theory to tunnels

From a systems perspective, we cannot discuss the fire safety levels of a tunnel without taking into account all the hierarchical layers, including owners, users, contractors, emergency responders, other stakeholders and the situational context (Santos-Reyes & Beard, 2001). Fire safety and accidents are considered properties of the system as a whole, i.e., properties which are only meaningful in an elevated hierarchical layer of control (Leveson, 2011; Rasmussen, 1997; Checkland, 1999).

Tunnel systems are complex, open socio-technical systems, meaning that they impose changes on, and are changed by, their environment (Checkland, 1999). It is therefore relevant to regard tunnels as adaptive systems operated within an envelope of safety, bounded by safety constraints (Bjelland et al., 2015). Effective safety management is about responding to system changes, using effective control mechanisms. For a road tunnel, such changes may for instance be: increasing AADT (NSIA, 2013; 2018), changes in traffic type, ageing components and subsystems, new energy carriers in vehicles, new digital technologies installed in tunnels, climate changes, etc. Recognizing such changes and their impact on the tunnel system and the processes we want to control is critical, in order to enforce relevant safety constraints. This is about knowing at all times the status of the tunnel system in relation to the processes that we are controlling.

For instance, the "evacuation process during a fire" is an example of a process that needs controlling. Identifying (parts of) the system that influence this process enables the interactions between system elements, actuators necessary to enforce constraints, sensors that feedback information about the system elements and the process' status, etc. to be modeled (Leveson, 2011). Our study of accident investigations in section 3 shows that tunnel owners, tunnel contractors/maintainers, tunnel drivers/users, TCC operators and emergency response personnel are important system actors influencing the evacuation process and, thus, should be subject to safety constraints. These actors interact with technical system elements, such as the fire detection system, the supervisory control and data acquisition (SCADA) system, the fire ventilation systems, the radio broadcasting systems, etc. Designing and maintaining such technical systems should take into account the scenarios that might occur, where continuous learning will challenge the selection of "dimensioning" scenarios.

Systems thinking is not necessarily a substitute for, but it may serve to complement, risk-based thinking (Kazaras et al., 2012). Different phases of a system's development or operation may need different management tools. The systems-oriented approach emphasizes the description of the system, the development of dimensioning scenarios and the identification of necessary safety constraints in order to keep the system in a safe state. Instead of looking for probabilities, uncertainties and adverse events, we look at road users' and emergency services' performances, to ensure that safety is controlled for the tunnel system.

4.2. Safety control structures

According to Leveson (2011), accidents are products of inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system. Accidents may occur due to 1) failure to identify hazards and safety constraints, 2) failure to maintain safety constraints, 3) inconsistency between process behavior and process models, and 4) lack of system state feedback in order to update process models. Fig. 1. illustrate that effective control of the evacuation process is dependent on adequate control actions during the planning/design and construction phases.

The self-rescue principle is an important design presumption for Norwegian road tunnels. Following this principle, the tunnel design shall be consistent with the capabilities of the road users and the emergency scenarios that might occur. The evacuation process itself is not under any systematic control or intervention, besides the road users' own control actions within the tunnel.

In tunnels, feedback from the various processes requires sensors. Norwegian road tunnels (at least the single-tube rural tunnels) are scarcely equipped with sensor technology. Adequate feedback from the process (emergency situation) is arbitrary, dependent on the individual actions of road users (sensors involve fire extinguishers and emergency phones, which may or may not be used). From the narratives of Oslofjord 1 and 2, it is found that vehicles enter the tunnel against red lights and closing gates. Similar findings are reported, e.g., in the Mont Blanc tunnel fire in 1999 (Shields, 2005). This indicates poor feedback from the incident and/or inadequate control actions by the traffic manager. The road users are simply not convinced that stopping is the best alternative.

There is a great potential to enhance safety, by providing better sensors in the tunnels and strengthening control of the evacuation process. People are reluctant to initiate immediate evacuation in the early stages of fire emergencies, but it also suggests that information is key to compensating for indecisive behavior.

5. Safety constraints for emergency management (response) in tunnels – A framework

In this section, the development of safety constraints from the use of fire investigations is discussed, and how to put such constraints into action. Adopting this approach to the N500 regulation will introduce major changes to existing compliance-based road safety management practices, but it will also embed the increased weight on the tunnel's emergency preparedness system into practical administration work. Current safety management practices are not described further than evidence from the narratives in section 3. This section deals with the framework to develop safety constraints for the emergency management system in tunnels.

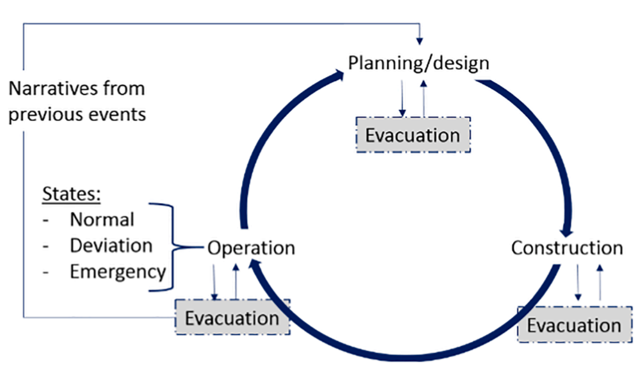

Fig. 1. Evacuation as a controlled process through planning, construction and operation.

5.1. Safety constraints

Developing safety constraints follows a systematic process involving five steps:

1. Define the system, including system boundaries and interactions with its environment.
2. Define the system's functional safety requirements.
3. Conduct hazard identification associated with the specified functional requirements.
4. Develop a set of valid scenarios, based on the hazard identification process, and conduct appropriate modeling to explore the boundaries and basis for safe operation. The validity of the scenarios is assessed by coherence principles, see Bjelland et al. (2015), which is not elaborated further here. However, narratives from real tunnel fires, which represent empirical evidence of what might happen, are strong coherence indicators (data priority, analogy).
5. Define the set of safety constraints necessary to keep the system in a safe state, i.e. to comply with functional safety requirements and to ensure that normal functions of the system are maintained. The derivation of safety constraints is based on both the hazard identification process directly and the scenario analyses and expressions signifying the level of accepted or prudent practice.

The notion or concept of constraints may easily be perceived by their negative connotations, and – not least related to establishing functional safety requirements and pointing at phenomena necessary to keep a system in a safe state – possible positive sides of the constraints may, thus, be left uncommunicated. Constraints stated through regulatory requirements are often expressed as utter limits for expected or allowable actions, performance or design traits. This is typical for regulations formulated as prescriptive requirements. When opening the door to regulations formulated by expectations related to performance, one may not merely present statements related to what at the least is to be achieved. There is even a possibility to present requirements stating that good, prudent or sound practice should be adhered to. The acceptable deviations from this "core" or "central" norm may vary, according to the overall performance of the system.

For example, the lack of effective mechanisms for the detection of a possible problematic incident must be compensated for by more effective mechanisms for other elements in the emergency preparedness. When applying performance-based regulations, coupled with an understanding of the relevant system, it ideally should be possible not only to optimize the balance between proactive and reactive emergency preparedness measures but even to arrive at a position to discuss the trade-off between costs and benefits related to maintaining safety, as well as functions, as expected in a given system.

Based on the scenarios described in the previous section, this section exemplifies a set of recommended safety constraints to keep the tunnel in a safe state. Safety constraints are logical developments from the Zero Vision strategy, politically enforced in Norway on September 29, 2000. Leveson (2011; 2019) distinguishes between system goals, constraints and requirements. System goals describe the basic reason for the system. A system goal for a road tunnel is, for instance, "transporting passengers and cargo from A to B". System constraints are the acceptable ways a system can achieve its goals. It may sound like constraints is another word for requirements, but, according to Leveson (2011), there is an important distinction. Specifying system requirements is a way of refining the system's goals. While system requirements cannot conflict with system goals, this is not the case for the system's safety constraints. For instance, denying access to HGVs in a tunnel, to limit the potential fire load, could be an example of a safety constraint that directly contradicts the system's goal.

Example: developing safety constraints for a road tunnel:

- Process: Emergency response to a single-tube tunnel fire

- Process goal: Prevent the event from developing into an accident that causes harm to tunnel users, structure, equipment and the environment.

5.2. Requirements to the set of and single constraints as part of the safety control functions

The safety of a system is "dependent on the enforcement of constraints on the behavior of the components in the system, including constraints on the potential interactions" (Leveson, 2011:64). The goal of enforcing constraints on a system's components is to maintain control, where *control* is the process of retaining the system's identity and performance under changing circumstances (Checkland, 1999:313). A control process entails the concept of hierarchy, where an upper level is imposing constraints on a lower level. The functions of the upper layer, e.g., a road tunnel's emergency response performance, emerge because of the imposition of constraints on the lower layers (Checkland, 1999; Leveson, 2011). Checkland (1999:87) specifies that a constraint should 1) "impose new functional relationships", 2) "be optimal in the sense that it is neither so tight that it leads to rigidity nor so loose that specific functions are not generated at the lower level", and 3) "act upon the detailed dynamics of the lower layer".

The following set of requirements should guide the specification of safety constraints:

1. They should be observable; they must be clearly defined and open for access when needed.
2. They should be measurable, i.e., it must be possible to verify their existence, non-existence or degree of existence. It must be possible to establish set points, limit states or criteria monitored by "sensors".
3. The controller is critically dependent on knowing the status of the controlled process. Hence, the controlled process must allow appropriate feedback about the status of the constraints to the controller.
4. They should be evenly distributed amongst actors involved with safety management, in order to reinforce collaboration in emergency response processes.
5. They should correspond to an available controller. If there is no controller to enforce the constraint, it is meaningless.
6. They should allow sufficient response and timely changes to the process/system due to exceeding constraints targets.

The following are examples of safety constraints enforced to avoid unsafe control actions for a road tunnel system. Following the five steps towards establishing safety constraints, it is assumed that the system is an existing long single-tube tunnel with bi-directional traffic, similar to the Gudvanga tunnel (NSIA, 2015; 2016a), with regard to characteristics of the safety equipment, emergency response system, etc. The functional requirements are related to the individual processes of emergency preparedness, cf. table 4. Finally, hazard identification and scenario selection are based on the accident investigation reports in section 3. The identification tag following the safety constraints, e.g. (1A), refers to the specific cell describing an unsafe control action in table 4. The intention of the examples is to illustrate the framework, and they will cover only the actors: general tunnel users, HGV tunnel users and TCC operators:

- Tunnel users in general shall…
  - o receive adequate information about the evacuation strategy of specific tunnels through training, information campaigns and intuitive design (1A).
  - o immediately (<1 min from observing the event) alert the TCC about fire location and situation (2A).
  - o receive in-vehicle information about the accident and preferred actions relative to available information about the event and the vehicle's location in the tunnel (3A).
  - o receive in-vehicle information about planned actions affecting the flow of smoke in the tunnel and preferred actions relative to the vehicle's location in the tunnel and smoke flow direction (4A).
  - o receive location-specific preferred actions supporting the self-evacuation process of the relevant group of tunnel users (5A).
- Tunnel users HGV shall…
  - o maintain and use in-vehicle systems to monitor vehicle fire risk, adopt safe driving behavior (e.g. maintain adequate distance) and produce and train for situational-dependent emergency protocols (1B).
  - o see 2A.
  - o see 3A, and take part in training programs to take on a role as a preliminary on-scene commander, reinforcing desirable self-evacuation behavior during the initial stage of an accident (3B).
  - o make sure that the vehicle has available automatic and/or manual extinguishment systems, dimensioned according to the relevant vehicle fire scenarios (4B).
  - o see 5A.
- TCC operators shall…
  - o maintain and use an appropriate system to keep track of the tunnel system's overall technical status, fault alarms and status of safety critical repairs (1C).

Table 4
Control-processes and related unsafe control activities as basis for constraints.

	Unsafe control activities (examples)				
Actors Control process	A. Tunnel users, general	B. Tunnel users, HGV	C. TCC operators	D. Emergency responders	E. Tunnel owners
1. Normal operation (Pre-accidental phase)	Unaware the evacuation strategies of different tunnels.	Unaware the fire hazard in HGV (risk status own vehicle).	Unaware the status of safety equipment, lack situation-dependent training.	Unaware tunnel-specific emergency response procedures and lack of training.	Failure to adapt tunnel system to a dynamic risk picture.
2. Detection and alert	Unaware intended function as detector and alert agents.	Unaware intended function as detector and alert agents.	Delayed detection and imprecise information.	Delayed detection and imprecise information.	
3. Mobilization and situational awareness	Lack information about the accident.	Lack information about the accident and training as on-scene commander.	Lack systems for information gathering and communication: fire, vehicles, people.	Lack information about fire location, vehicles and people.	
4. Combat and smoke control	Unaware ventilation strategy.	Inadequate fire extinguishment equipment.	Lack information. Lack situation-dependent protocols.	Lack information. Lack situation-dependent protocols. Poor communication.	
5. Evacuation and rescue	Lack of information, risk awareness and time. Unaware the evacuation strategy in specific tunnel.	Lack of information, risk awareness and time. Unaware the evacuation strategy in specific tunnel.	Lack information and means of communicating with people in the tunnel.	Lack information and means of communicating with people in the tunnel.	

o within 1 minute after the initiating event, detect a potentially major fire in the tunnel system and verify the fire source and consequence potential (2C).
o within 2 minutes after detecting the fire, obtain an overview of the number and location of vehicles in the tunnel and activate a first warning to tunnel users. Within 3 minutes after detecting the fire, prepare location-specific group-messages to tunnel users (3C).
o within 4 minutes after detecting the fire, select a situation-dependent strategy for smoke control, on the basis of available information about the fire, vehicles and people (4C).
o within 5 minutes after detecting the fire, inform tunnel users about the strategy for smoke control and associated consequences and also inform about preferred actions relative to the tunnel user's location (5C).

Following this approach while designing an emergency response system will lead to consistency between the hazard identification process and the system's control structure. Time constraints are intentionally included, as this will challenge existing design and emergency response practices and technical solutions. This will effectively create new possible systems that need evaluation against dimensioning accident scenarios, limitations in available technology and cost-effectiveness.

6. Discussion

The level of system knowledge amongst the Norwegian tunnel safety actors is low. Knowledge about the contents of goods travelling through Norwegian tunnels is scant. This is especially true regarding the potential for exposure to toxic substances in serious releases and combustions. The tunnels are socio-technical systems, not very easily predicted in the case of future accidental events. As regards tunnel owners and the emergency services, the level of complexity is challenging for their safety management work. To a certain extent, risk analysis approaches address simplified systems, which, for tunnels similar to the Oslofjord tunnel, might not be sufficient to optimize safety and provide useful decision support (Njå, 2016).

Njå & Svela (2018) suggest that tunnels should be subject to "Safety Case" regulations, for which the tunnel owner, in close cooperation with the rescue services, needs to demonstrate adequate safety systems and emergency response. In this respect, establishing safety constraints would contribute to a holistic safety system. The tunnel owner is responsible for tunnels being adequately equipped with emergency preparedness measures, allowing firefighting and rescue operations. Expectations and capacity regarding the local fire service need clarification, and the tunnel must be equipped accordingly. Our view is that society expects the fire department to push limits to fight a fire in the tunnel and rescue people. The fire department also seems to place high expectations on themselves, taking more than "their share" of responsibility in major tunnel fires. The fire department's actions in the Gudvanga 1 fire corroborate this, with personnel from the fire department defying thick smoke to search the tunnel.

In many municipalities, a local voluntary fire department is responsible for the emergency preparedness and executive response to major road tunnel fires. The emergency preparedness analysis should recognize the emergency responders' limitations and design the tunnel accordingly. However, it could be questioned whether this is the practice today. We question both the local voluntary fire department's competency, with regard to understanding their own limitations, and the current emergency preparedness analyses' ability to identify weaknesses and compensate for them by means of safety measures in tunnel design. In other words, the tunnel design does not match the emergency response capacity, which may lead to an emergency response that does not match the situation in the tunnel. This is a clear example of safety constraints being violated.

Compared with road tunnels, the number of fires in Norwegian railway tunnels is low. Nevertheless, there has been a rather heated professional debate over emergency preparedness measures. On one side, the emergency response authorities and local fire departments argue that mechanical fire ventilation and water supply for fire extinguishing is critical in railway tunnels. *Their* dimensioning scenario is a serious fire in a train inside a railway tunnel. On the other side, the tunnel owners argue that such emergency response measures are not relevant for *their* dimensioning scenarios. The tunnel owner puts more weight on the fire protection of trains and the train's ability to drive out of the tunnel in case of fire. Recently, RISE Fire Research issued a report about dimensioning fire scenarios in railway tunnels on behalf of the Norwegian tunnel owner. Although there is uncertainty about fire behavior in modern trains, the report recommends a design fire of 20 – 60 MW and a "fast" fire growth rate. RISE cannot exclude the possibility of a fire occurring in an immobilized train in a tunnel, although the frequency of such events will be low (Meraner et al., 2020).

It is interesting to follow this discussion, as it points to the question of how to define dimensioning scenarios for tunnel design and emergency response, which is a relevant question for both road and railway tunnels. To what degree is selecting dimensioning scenarios a matter of scientific rigor or value judgements? Our view is that this ultimately is a value judgment, informed by scientific knowledge. Adopting a system perspective should clarify the links between the different actors in the system and make explicit how top-level value judgements affect the design of emergency preparedness systems in road tunnels. Being clear about the actors' different responsibilities is a good starting point for strengthening emergency preparedness in Norwegian road tunnels.

Finally, the importance of *control* as the major goal of the systems perspective on safety is repeated. Open socio-technical systems, such as road tunnels, are inherently dynamic. Control in such systems then, is more like a thing that you borrow than a thing you own. Maintaining the control in the system requires constant measuring of the status of the system's elements, continuous learning from its operation, and implementing learning from previous events, new research and new technologies. Understanding important principles that affect safety, such as the self-evacuation principle, is important. Systems thinking clearly shows how it is an inter-disciplinary task to safely control evacuation processes. This should be a driver to replace current silo thinking with more collaboration. Systems thinking for road tunnel safety will require many actors doing things differently. If there is one thing that we can learn from previous events it is that continuing without changes will lead to new major accidents.

7. Conclusions

Successful emergency response to tunnel fires is dependent on many actors collaborating on avoiding losses. When a fire incident occurs in a road tunnel, time is of the essence. Safety becomes a matter of maintaining the critical processes necessary to keep the system in a safe state. There is little time for planning and weighing different options while managing an accident. Efficient decision-making, in situations of major uncertainty, is vital to achieve safety goals. This essentially means that efficient emergency preparedness for road tunnels is a matter that needs attention in the early design phase and continuous improvements during the operational phases.

Emergency preparedness analyses are required in the design phase by Norwegian legislation for tunnels greater 1,000 meters. Guidance and functional requirements are lacking. The combination of a micro-means-based (prescriptive) regulation regime and strong traditions and expectations regarding emergency response leads to arbitrary emergency response performance, determined by standard tunnel design solutions and the capability of the local emergency response. The latter involves major variations, depending on the location of the tunnel.

To achieve high-performance emergency preparedness for major tunnel fires, there is a need for radical changes in designing and operating tunnels. Management should shift from being compliance-based to being functionally based, including clear performance requirements for the emergency response system. Taking into account the complexity of emergency response to road tunnels, such a regulative framework would lead to changes in tunnel designs, especially in order to accommodate road users' and local emergency response teams' different capabilities. In this paper, it is claimed that a system-theoretic approach is appropriate to deal with the tunnel system's complexity and drive the design of appropriate control structures for critical processes from the design phase to the actual emergency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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