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A review of competencies in tunnel fire response seen from the first responders' perspectives

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A R T I C L E I N F O

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A B S T R A C T

Norway has an increasing number of long and complicated road tunnel designs, which can be defined as complex sociotechnical systems. To avoid major accidents and fire situations, knowledge about the fire safety is required by both the fire and rescue services and the society. This article focuses on how representatives from fire and rescue services express uncertainties and expectations regarding the knowledge dimension of the road tunnel fire and rescue systems. The article is based on investigations of two tunnel fires in Norway, in addition to data from a workshop with tunnel fire response experts. The data has been analysed using systems engineering approach combined with an understanding of learning. This study has revealed tunnel fire safety concerns related to the Norwegian emergency response personnel's state of competence both in the pre- and post-accidental phases. The situation regarding tunnel fire safety is unclear and fragmented, with corresponding weaknesses in the existing knowledge. The future will bring even more complex road tunnels, also subsea-crossings, that challenge all parties: road owners, road users, vehicle producers, emergency responders and authorities. Norway needs facilities for tunnel safety training that can complement existing facilities and provide new knowledge.

1. Introduction

In the wake of the tunnel disasters in Tauern, Mont Blanc and St. Gotthard some 15 years ago, the fire events and safety management systems in the Oslofjord tunnel (23 June 2011 - [1]) and the Gudvanga-tunnel (5 August 2013 - [2]) have been critically considered by the Norwegian society. The Accident Investigation Board Norway (AIBN) has carried out its investigations with the aim to provide lessons learned. Of particular concerns are the interactions between the public roads authorities, the tunnel systems, the emergency response systems and the road-users. The society does not accept fire disasters in road tunnels, thus there is a demand for knowledge about the fire safety. The stakeholders within these systems have a common goal to avoid major accidents and fire situations. However, albeit the good intentions, the current status of knowledge is restricted to few events, some experience data from traffic accidents, experimental tests from low scale facilities, exercises and fire simulation tools. In Norway, the Runehamar tunnel is a full-scale test tunnel. This tunnel has been employed for various fire experiments and research projects [10,16,17,3,9].

Norway has an increasing number of long and complicated road tunnel designs. Today the road infrastructure consists of over 1000 tunnels. There are 33 subsea tunnels and 24 mountain tunnels with steep slopes (>5%), and these tunnels comprises 5% of the length of the Norwegian road tunnels [19]. Subsea tunnels have no entrances beside the tube and they are long with often steep slopes. The Norwegian Government has decided to build the world's longest and deepest subsea road tunnels. When the Ryfast tunnel is complete in 2019, it will be 14.3 km long, 290 m below sea at the deepest, with a maximum gradient of 7.9%. Five years later the Rogfast tunnel is scheduled, with a planned length of 26.7 km, a depth of 390 m below sea and maximum gradient of 5%. Both tunnels will be dual tube.

According to numbers retrieved from the five Traffic Control Centres in Norway, 42% of the registered tunnel fires in Norway in the period from 2008 until 2015, occurred in these 57 tunnels described above. Heavy goods vehicles (HGV) were involved in most of these fires, mainly caused by technical malfunctions [19]. The fires in the Oslofjord and Gudvanga tunnels in 2011 and 2013 both started in HGVs. And, both tunnels are bi-directional single tubes, they have steep slopes and primary emergency exits through the tunnel portals. Another situational resemblance in the events was the location of the fire related to the ventilation direction, which caused smoke spreading in large portions of the tunnels. There were no fatalities in the fires, but many people were

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trapped in the smoke; 34 in the Oslofjord tunnel [1] and 67 in the Gudvanga tunnel [2], many which sustained acute smoke injuries and psychological traumas. Neither the tunnel-owners nor the rescue services were in control of the smoke flows and the concentrations of toxic gases in those events.

The road-users' expected emergency response behaviours in tunnel fires is based on the *self-rescue principle*. This means that the road-users are supposed to evacuate from the tunnel themselves, either by car or by foot. Experiences from the tunnel fires mentioned are that not all road-users evacuate. Some of them stay in their vehicles (mostly HGVs) with recirculating air condition [1,2]. Professional rescuers are on call and the predominant approach is to extinguish the fire as soon as possible in order to provide access for the rescuers to reach people trapped in the tunnel. In single tube tunnels, the fire ventilation is a vital tool for the firefighters to provide access to the fire, and significantly dilute the smoke concentration downstream to improve the conditions for the evacuating people. The fire ventilation direction is usually predefined, based on the idea that the most capable fire department shall be in charge of the fire and rescue operation. However, the fire and smoke dispersion modelling and related validation as basis for the strategy chosen is scarce, and there has been a major discussion whether this strategy is better than suppressing ventilation in order to increase the time margins for all road-users with urgent need for evacuation. A predefined fire ventilation might also contribute to fire spread to other vehicles downstream.

Existing literature on tunnel fire safety addresses aspects like smoke, ventilation, fire dynamics, design fires, construction, risk assessment etc., but the rescue and firefighting operations performed by the fire brigades have generally received less attention [12]. The first response services need to understand and comprehend the complex systems and related design fire scenarios in order to be able to optimise their performance [4]. There is a need to convert and communicate such knowledge to the first response personnel in a way that makes it relevant for their working situations and experiences. Tunnel fires are rare events, and actual experiences from such scenarios are scarce.

The limitations of fire and rescue operations in tunnel fires has been the focus of previous research projects [21]. Kim et al. [12] have developed general operational procedures and proposed a classification model for firefighting in road tunnels. The study establishes some key elements for fire and rescue operations in road tunnels: choice of strategy; obtaining necessary information; access route and approach distance; control of air flow; rescue operations; cooperation between fire brigades at different portals and jurisdictions; and operations under fixed fire suppression systems. They suggest a classification model to help diagnosing *"the risk status of each road tunnel from the fire brigade's point of view and to determine the proper solution to decrease the risk level"* (p. 60). Four parameters are suggested for classifying the tunnels: passage of HGV and vehicles carrying dangerous goods (1), type of tunnel (2), risk of congestion (3) and response time (4).

Research from Sweden has revealed how tactics and methods for firefighting in underground facilities can be adapted to the risks, and how these risks can be defined [11,21]. Results from the full-scale firefighting tests in the Tistbrottet Mine in 2013 emphasize that the available amount of breathing air is an important limiting factor in fire and rescue operations under ground. The tests also showed that time spent on organizing the team and arranging equipment were substantial compared to the time spent on walking. Time is a crucial aspect in every firefighting operation, and the test results indicates that there should be a focus on improving the equipment handling and team management. The use of IR image cameras proved necessary, but the tests also showed a need for adapting the usage of such tools to underground facilities, as well as training the users. The project points at the possibility of using reconnaissance teams as an alternative method for information gathering. This would not be in accordance with existing Swedish or Norwegian legislation, but are suggested for closer studies [18,20,21].

The study presented in this article challenges the knowledge dimension of the road tunnel fire and rescue systems in Norway, including the individuals involved. In this study knowledge is related to phenomena, tasks, communication and interaction abilities, and how the actors approach tunnel fire safety in general. By the term "actor", we mean any agency or person involved in the emergency management of road tunnels. We were interested in how representatives from responsible road tunnel fire and rescue services expressed their uncertainties and expectations. We analysed the data material in a systems engineering approach combined with an understanding of learning addressing change, confirmation and comprehension of the crisis response systems.

2. Systems engineering theory to safety management

2.1. The Norwegian tunnel fire and rescue services

The municipalities govern the fire and rescue services in Norway. The 428 Norwegian municipalities range from only 200 inhabitants to 600,000 in the largest. Some municipalities have engaged in partnerships regarding operation of the fire and rescue service. In 2013, the total number of fire and rescue services was about 295; 26 were organised as inter-municipal companies, 205 were independent, and the remaining were involved in some kind of cooperation with neighbouring municipalities. The smallest fire and rescue services cover less than 3000 inhabitants while the biggest cover more than 250,000 [30].

The Norwegian preparedness structure is founded on four principles: *responsibility*, *proximity*, *similarity* and *cooperation*. These principles states that those who are responsible for and involved in day to day crisis management, at all levels, are tasked with the same responsibilities and works during major tunnel fire events as in the daily work. The cooperation principle is especially interesting, and it implies that authorities, voluntary, private and official actors are individually responsible for establishing appropriate interactions with relevant parties regarding the fire and rescue situations. Good cooperation between the different actors in the tunnel system is vital for the planning and performance of the fire response. The public roads authorities, the fire and rescue service, the police and the ambulance service must agree on and understand each other's roles and responsibilities. Establishing effective emergency response cooperation requires coordinated response plans, procedures and routines as well as regular exercises and training involving all relevant parties. Thus, the knowledge and competencies within, across and along organisational units is of vital importance.

2.2. Complex sociotechnical systems

The term sociotechnical includes the interaction between social and technical factors when describing conditions underlying system performance [32]. Trist [31] refers to the Tavistock studies of the British coal mining industry when he draw the evolution of the socio-technical system (STS) approach. STS was analysed at three levels; the primary work system, the whole organisation and the macrosocial phenomena. Modelling sociotechnical systems has often taken the form of structural decomposition, where the system is decomposed into individual elements, and its function is described by the causal interaction between these elements [23,24]. Such models seek to control the system's activities and safety through a top-down command-and-control approach. Traditional top-down control mechanisms consist of laws, regulations, standards, procedures, routines etc. which strives "*to control behaviour by fighting deviations from a particular pre-planned path*" ([23], p. 191). These mechanisms are subjected to contextual interpretation and implementation by the different actors at each system level depicted in Fig. 1, giving rise to excessive margins in the control mechanisms [23]. Several researchers have argued that such decomposition and top-down control is only effective in a stable environment, and not sufficient in order to

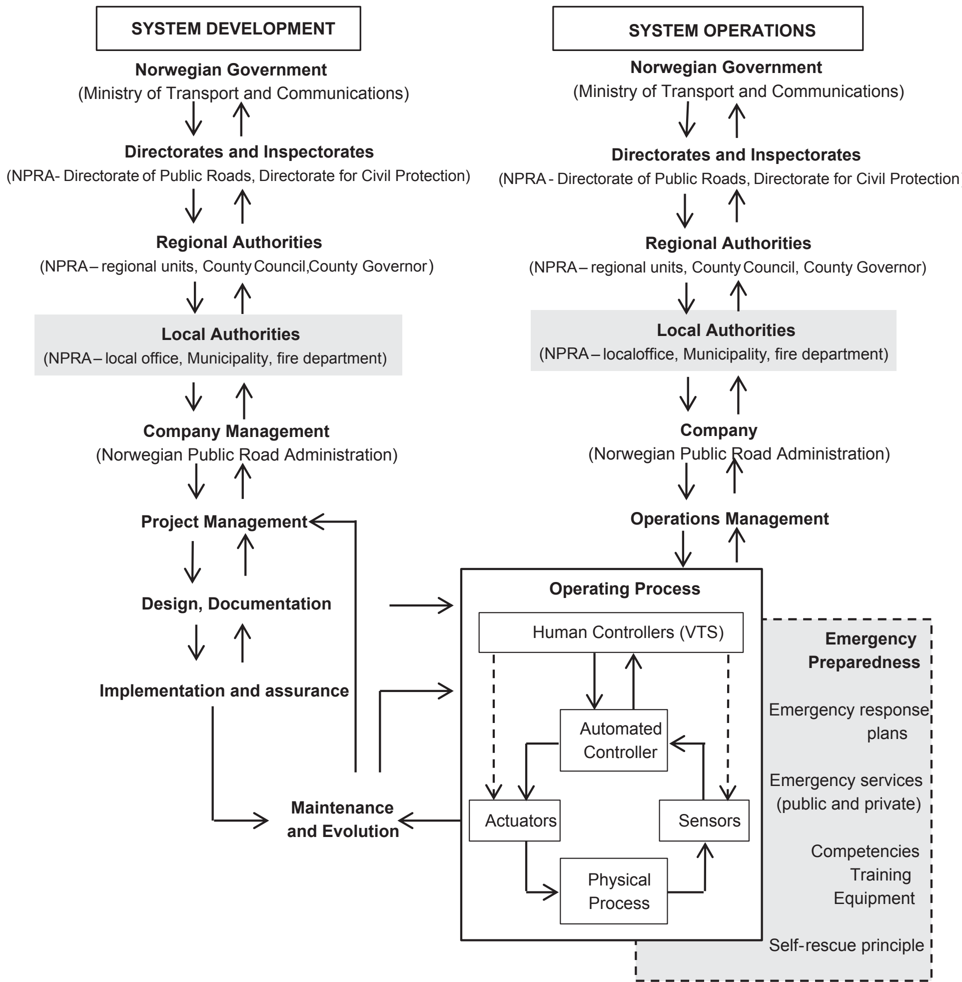

Fig. 1. Road tunnel systems based on Leveson's model (2011, p. 82).

control the systems performance given today's dynamic society, rapid development and high degree of integration [14,23,24]. From the early 2000, the Norwegian Government implemented the Zero Vision philosophy to traffic safety, which implied that the Norwegian Public Roads Administration had to adopt a systems approach to safety, influenced by Swedish works and the safety management of the Norwegian oil and gas industry. Systems theory has been an important paradigm shift to the road traffic sector [13].

An interesting development is presented by Nancy Leveson [14] who claims that the complex sociotechnical systems of our society require a safety management approach based on systems engineering. The approach views the systems and accident factors holistically instead of decomposed into individual components, units or subsystems malfunctioning in linear processes. Such a holistic view is also emphasized by Lönnermark et al. [18] regarding the design phase of a tunnel, and the importance of involving the different actors early in the design processes. Events, actions and the behaviour of different components can only be understood by considering its *"role and interaction within the system as a whole"* ([14], p. 70). Safety is seen as a control problem solved by imposing constraints upon the performance of the system in design and operation. *"Constraints represent acceptable ways the system or organisation can achieve the mission goals. Not exposing bystanders to toxins and not polluting the environment are constraints on the way the mission* (this case: transport through road tunnels) *can be achieved"* (p. 11). Safety constraints are provided through hierarchical structures, cf. Fig. 1, *"where each level imposes constraints on the activity of the level beneath it"* (p. 80), and thus form the framework for practice and performance. This hierarchy of control is based on adaptive feedback mechanisms and communication to ensure that *"the information needed for decision making is available to the right people at the right time"* (p. 307).

Perrow [22] characterises complexity by interactions in systems: *"unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible"* (p. 78). Leveson [14] nuances complexity and describes different forms related to: interaction among system components (*interactive complexity*); changes over time (*dynamic complexity*); structural and functional decomposition not being consistent (*decompositional complexity*); and no direct or obvious relation between cause and effect (*nonlinear complexity*). All underground structures can be characterised as complex environments due to differing risk pictures compared to other confined fire situations, the response-routes are often long, combined with a lack of overview [21].

The road tunnel system can be defined as an open system constantly affected by its components and the surrounding environment. Norwegian road tunnels have special characterisations affecting the ability to combat and rescue from tunnel fires, such as length, gradient, location, high traffic volume, high proportion of HGV traffic, fuel composition, number of people trapped, technical and organisational safety measures, knowledge etc. The different components in the tunnel system interact in various ways that are difficult to understand, and can result in escalating fire incidents. The fire and rescue services' ability to predict such incidents is associated with considerable uncertainty. Our connotation of "complex tunnel systems" includes the abovementioned characteristics.

Examples of complex road tunnels are thus long bi-directional single tube tunnels with emergency exits only through the tunnel portals, subsea bi-directional single tube tunnels, densely crowded dual tube tunnels and long subsea dual tube tunnels. Complexity seems to increase and makes it difficult to understand the systems' potential behaviour. Thus, Leveson [14] defines complexity as *intellectual unmanageability*. Epistemology is a vital dimension.

We conclude that many of the Norwegian road tunnels are complex sociotechnical systems; a system description is presented in Fig. 1. The Norwegian government and the Ministry of Transport and Communications constitute the top level in a road tunnel system. This level develops and maintains the legislation and chooses regulation regime. The levels beneath comprises Directorates and regional and local authorities which administers regulations, standards and guidelines regarding safety requirements for road tunnels. The Norwegian Public Roads Administration (NPRA) is a complex organisation having responsibilities and roles from directorate level to detail planning and building of tunnel systems, as well as operations and maintenance of the same systems. The Norwegian Directorate for Civil Protection administers regulations, inspects and supervises organisation and dimensioning of the municipal fire and rescue services. The municipal fire and rescue services are involved in both the planning and operations of the tunnel systems, for example they participate in planning processes and risk assessments, and they constitute an essential part of the tunnel systems' emergency preparedness during both construction and operation. The fire and rescue services also function as supervisory authorities of the road tunnels in their area (municipality/-ies) regarding fire safety, considering preventive measures or mitigation. The fire and rescue services thus need comprehensive knowledge about the tunnel systems. Leveson [14] claims that the systems are exposed to variation and changes in the environment and will subsequently evolve and change over time. The tunnel system will for example be exposed to variations in annual average daily traffic (AADT), distribution of heavy goods vehicles, ageing, fouling and road users' driving behaviour.

The tunnel systems contain a high number of actors with a common goal to avoid major accidents and fire situations. The feedback mechanisms depicted in Fig. 1 provide decision makers on each level with opportunities to learn from accidents, incidents, analyses, inspections and audits. Good information about potential causes of accidents in the system and the state of implemented control mechanisms is necessary in order to establish a knowledge based risk perception [14]. Investigating incidents and accidents is not enough; such processes must be followed by recommendations and assignment of responsibilities for implementing lessons and knowledge provided.

2.3. Learning and training

Learning is central in systems thinking applied to safety, and human behaviour is seen as *"a product of the environment in which it occurs"* ([14], p. 47). Rather than assuming that most accidents are caused by human errors and violations, Leveson [14] emphasizes contextual mechanisms that generate behaviour, and performance of safety constraints. Thus, it is important that everyone involved in the safety control systems understand the rationale behind the systems design, including their own roles and responsibilities. Knowledge regarding potential hazards associated with the operation of the system is necessary to make people able to recognize precursors to accidents. The system operators must *"have an in-depth understanding of the controlled physical process and the logic used in any automated controllers they may be supervising"*, an understanding that involves much more than learning procedures ([14], p. 411).

The first responders are an essential part of the tunnel system's operational safety. Sommer, Braut, and Njå's [28] model for learning in emergency response work combines socio-cultural and individual cognitive premises. This model sees learning as *"changes in structures, behaviours or working methods, confirmation of existing knowledge and/or comprehension of existing practice"* (p. 151). The learners are the individual actors, and it coincides with Leveson's [14] view on human behaviour as a product of the surrounding factors. Learning is described as a continuous process where experiences mix with *continuous reflection, controlled exercises, training* and *lecturing activities*, and the contents are both practical and theoretical. The emergency organisation's traditions, culture and the embedded knowledge influence how the individuals think and behave in fire and rescue situations. Sommer et al. [28] also state that the goal for learning in emergency response work is to make emergency workers able to consider relevant cues in their decision-making. The same account is made by Leveson [14] when she argues that *"decision makers at all levels of the safety control structure also need to understand the risks they are taking in the decisions they make: Training should include not just what but why"* (pp. 410–411). This also yields the first responders in action on site, who need to be flexible assessing situational demands, but at the same time having internalised the procedures and interacting practices. These properties were demonstrated at the Elstangen command point for receiving evacuees from Utoya Island during the terrorist attack in Norway 2011 [25].

3. Study approach

In this study, we challenge the knowledge dimension of the road tunnel fire and rescue systems. The data material is gathered from two sources; 1) two fire event cases – the Oslofjord tunnel fire (2011) and the Gudvanga tunnel fire (2013); and 2) a workshop in June 2015 at the Societal Safety Centre in Rogaland (SASIRO). The study reflects the challenges with tunnel fire safety seen from the first responders' points of view about competencies and knowledge of the different organisational levels in the tunnel system. Our analytical dimensions are uncertainties and insufficient abilities to respond to tunnel fire events, based on the inputs from the workshop participants and the written material from the events. We define uncertainty as something that can be doubted, discussed or even not known, related to tunnel fire safety. We could categorize uncertainties, see for example the framework of Lipshitz & Strauss [15], but we have omitted this in order to highlight the contents and stories of uncertainties. Insufficient abilities are the first responders' own views of lacking capabilities to conduct necessary tasks.

The workshop was organised by Rogaland Fire and Rescue, the University of Stavanger and the Norwegian Public Roads Administration (NPRA). The 26 participants had experiences from fire prevention, supervisory activities and planning processes regarding road tunnels, and/or firefighting, rescue operations and incident command in tunnel fires. They were mainly representatives from different Norwegian fire and rescue services (18) and ambulance services (2). In their work, all operational personnel were subjected to complex road tunnels. In addition there were participants from the NPRA, Directorate for Civil Protection, academic institutions, a private consultancy company, and a transportation company (6 in total) with tunnel fire safety experience from research, regulation, fire prevention, supervisory activities, planning processes and transport activities. The participants represented only some of the levels in the tunnel system's operation structure, mainly depicted in Fig. 2, of which we restrict our analysis.

The workshop was organised with two group sessions and the participants divided into three different groups. In the first session the groups were asked to elaborate on their personal experiences from real incidents or training in complex tunnel systems. The discussion focused on situations that represent great challenges for the fire and rescue service today, critical phases in the rescue operation and the interaction with other actors (emergency services). The second session focused on lacking and inadequate knowledge regarding situations and conditions related to road tunnels, how this challenges the Norwegian emergency response system, the need for enhanced knowledge and how to achieve better competencies in order to meet critical tunnel fire situations. All the group sessions were recorded and transcriptions made subsequently. The written material comprised of various reports and evaluations made after the tunnel fire accidents in the Oslofjord tunnel on June 23rd, 2011 and

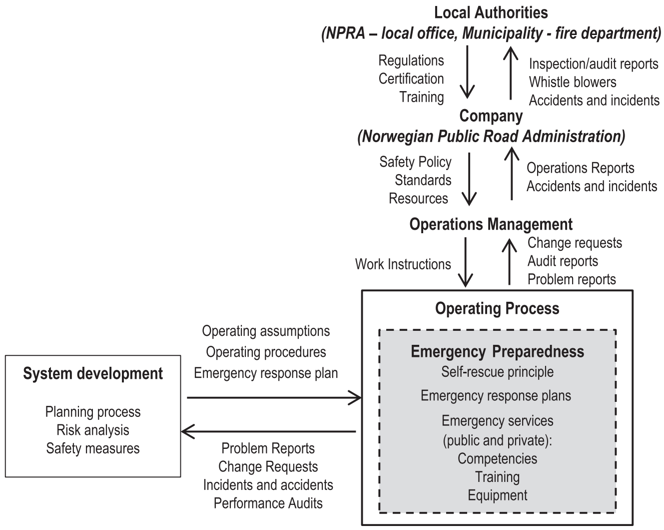

Fig. 2. Extract of the road tunnel model for data analysis.

the Gudvanga tunnel on August 5th, 2013. Also here knowledge and competencies were basis for the analysis of uncertainties and inabilities to respond sufficiently, with special attention towards the reports' analyses of the fire and rescue services roles and responsibilities.

4. Concerns about tunnel fire safety

We split the findings from the workshop and events into pre- and post-accidental phases and their subsequent uncertainties and insufficient capabilities. The weight is put on first responders' perspectives, and we do not elaborate on critics from the accident investigations addressing omissions or erroneous commissions of tasks by the tunnel owners.

4.1. The pre-accidental phases

These phases include all aspects before detecting a fire situation. Being at this stage, the design principles, motivational and competence philosophies related to personnel, organisational development, etc. are important arrangements. Thus, it includes all scenarios that govern the tunnel preparedness levels and the operation and maintenance of the tunnel preparedness systems.

4.1.1. Uncertainties

Neither the workshop participants nor the data material from the events provided information about the traffic conditions, the road-user behaviour or the goods that travelled through the various complex tunnels. Some mentioned the annual average daily traffic (AADT) and other the portion of HGVs as measures they meant were important. How these measures relate to the tunnel designs and their own responsibilities were not discussed at all, thus the relation between AADT, HGV distributions and fire accident scenarios is unknown to first responders. One workshop participant from the eastern part of Norway claimed that 90% of the HGV coming to Norway at the border between Norway and Sweden were foreign vehicles and generally understood as having lower technical and operational standard than the Norwegian HGVs. Also from the eastern part of Norway, major concerns were related to congestions, their occurrences and how people behave in critical situations given congestions.

Risk and vulnerability analyses as planning tools for tunnel fire safety were criticised by many participants. First of all the probability concept and messages from analyses were emphasized as problematic. For example, analyses saying that frequencies of major events is one per 300 years was regarded ridiculous and not of any use to them. The uncertainty seems to be more related to concepts, purposes and characteristics with the analysis tools than contents of modelling and the data material employed. Concepts such as risk, design fires, heat release rate and megawatt are difficult for first responders to grasp and relate to their firefighting and rescuing activities. The representatives from the fire and rescue services that had been involved in risk analysis processes were less critical, but they did not object to those who criticised the analyses. One representative said that in the eastern Norway risk analyses assumed the firefighting units to be in action within four minutes, which he said was a false premise. There seem to be major ambiguities on how the fire and rescue services should design their combat systems and develop frameworks for their emergency response. Furthermore, which toxic, heat and psychological exposures must be included in the tunnel design and addressed to the various parties, is an unanswered question.

Ventilation strategies were considered a big issue at the workshop when discussing preparedness measures. Concerns and uncertainties were forwarded due to functionalities of the ventilation systems of their respective tunnels and whether there might be a universal and right solution to this issue. One representative from the preventive and supervisory part of the fire and rescue services claimed that the experts gave different advices, and he was supported by others who said that there were too much subjectivity in expert assessments, too many studies and reports that they could not transfer to applicable measures. Another similar representative claimed that the NPRA did not maintain its equipment and that inspection reports were neglected. Failures of the ventilation systems were often experienced with the many old and narrow single tube tunnels in western Norway. Representatives from northern Norway also complained about lacking communication with the NPRA and thus the lack of mutual understanding of challenges within their tunnels. Mobilisation time for the firefighting units for some of the tunnels was said to be approximately one hour, which was regarded as meaningless with respect to saving lives.

Personal experience seems to be very important as a reference for expressing magnitude of crisis contents and uncertainties involved. One physician experienced a major accident with a Swedish bus hitting a tunnel wall nearly 30 years ago. A big accident killing 16 persons of which 12 kids, many of them were crushed to death. It was a mass casualty situation putting heavy loads on triage, treatment and first response activities. This representative had a very humble attitude to the phenomenon tunnel fires, causing stressful situations with heavy noises, severe heat conditions and difficult working situations. He saw no other solution than developing training programs preferably involving all the cooperating emergency response actors. Frequent training was regarded a prerequisite to cope with tunnel fire situations in the future.

The local fire department's supervision activities of the Oslofjord tunnel began well before its operation phase (June 2000) and the findings were that the tunnel's safety equipment did not ensure personal safety for road users and rescue personnel. The fire chief issued directives regarding CCTV monitoring of the Oslofjord tunnel already in 2000. NPRA refused to comply, and the Directorate of Civil Protection supported NPRA's appeal. During the following years, the fire department several times requested updated risk analysis and emergency response plans. At one occasion, the NPRA replied that the existing risk analysis from the planning process was considered sufficient. During the investigation process after the fire in the Oslofjord tunnel the local fire department passively committed that they did not possess special expertise regarding fire risk in road tunnels and thereby no basis for overruling the risk analyses done by the tunnel owner [1]. Thus, it could seem that the risk analyses were more a tool to confuse rather than clarify safety issues for the fire and rescue services.

4.1.2. Insufficient capabilities

Some workshop participants believed that the fire and rescue services would need comprehensive and reliable knowledge about the tunnel fire safety subject to meet and correct the dominant NPRA in planning processes and supervisory activities. The experiences shared at the workshop pointed at the need for better quality in the supervisory reports when presenting deviations found trough inspections and audits. This would provide the fire and rescue services with a better tool to influence NPRA's safety efforts. The AIBN, in their investigation report after the Oslofjord tunnel fire also points to the need for adjusting the fire department's supervisory role to provide a better corrective in relation to the NPRA's safety management and manuals [1]. It is difficult to comprehend the AIBN's justification of its statement, but it is a structural problem that the supervisory authority (the fire department) lacks instruments in order to enforce the tunnel owner to follow up deviations and safety problems presented in inspection reports. A workshop participant referred to an audit he made in his region, where he claimed that his comprehensive comments regarding weaknesses of the technical safety systems were completely neglected. He said that he had now come to a conclusion that inspections was waste of time, changes to the tunnel equipment must be achieved by other means, for example concrete testing and demonstration activities. However, the AIBN faces the same structural challenges as the fire and rescue services when the agency submit its report to the Ministry of communications and transport. The AIBN cannot follow up its own recommendations. The investigation of the Gudvanga tunnel fire refers to a risk analysis conducted by the NPRA in April 2013, which identified the same critical scenario that occurred four months later, and it pointed out that the NPRA thus was familiar with the tunnel's poor safety level. The investigation board found that the supervisory audits done by the local fire department in the Gudvanga tunnel were not appropriate to identify safety critical factors for the self-rescue premises, because there were only conducted system audits and no on-site inspections [2].

Even though there is a requirement to carry out risk analysis for all tunnels longer than 500 m, participants at the workshop referred to the prevailing codes and norms providing pre-accepted solutions. In this way, actors in the tunnel design phase do not challenge the safety level, but mere keep a compliance perspective. The design of the emergency response systems is not subjected to scenarios that are governing the design. The AIBN argues that the fire department could be more involved in the drafting of the emergency response plans for road tunnels [1]. A representative from the fire and rescue service from the western Norway said that the emergency preparedness plans were of low quality, not coherent, not related to reliable and validated performance assessments and often with standard information impossible to apply for designing specific operations procedures. Performance analysis of emergency preparedness measures was said to be very rarely seen and in fact the workshop participants only knew of a single one related to the Rogfast project (cf. section 1).

4.2. The post-accidental phases

These phases include all aspects after detecting a fire situation. Thus, it includes all systems established to respond to fire and crisis situations in tunnels. If no or inappropriate corrective compelling actions are taken, the consequences will become severe. In order to clarify competencies we analysed the data material for uncertainties and lacking capabilities in the response activities.

4.2.1. Uncertainties

The workshop gave a clear picture of the *great variation* across the country, due to both the organisation and dimensioning of the fire and rescue services, but also the safety level in the road tunnels. Entering tunnels filled with smoke is a major problem for firefighters. Their self-contained breathing apparatus will only last for approximately half an hour after entering the tunnel, which implies major uncertainties regarding the firefighting and rescuing performance. Another ambiguity and difficult concept is the principle of self-rescue. Many participants from the fire and rescue services expressed uncertainty regarding this concept and the understanding of it, when designing the response strategies. Nobody seemed to have experienced the self-rescue principle as an integral part of their planning processes, but some participants stated that it is not possible to equal the self-rescue principle in buildings (industry, shopping centre, residential houses) with tunnels (often more than 5 km long).

Firefighters that approach a tunnel with smoke coming out of the portal face major uncertainties. There might be no communication means working, the functionality of the ventilation systems is unclear, water supply is of concern etc. Other uncertainties are both related to fire intensity and toxicity, which for the incident commander and fire chief is complicated due to critical assessments of the health issues of the first responders in action. This is an explanation of why the ventilation strategy complies with the immediate action from the predefined firefighting department set up to access the fire, independent of where the fire is located. The drawback of this strategy is that it does not coincide with the self-rescue principle and neither a performance based emergency response system. A major uncertainty is; what influences decisions made in fire scenarios?

The fire ventilation was a much discussed issue at the workshop. There was a consensus among the different fire and rescue services of the need for more knowledge regarding fire ventilation strategies. Today various experts hold different theories and recommendations. The AIBN is as uncertain as the other parties are, and it cannot provide scientific based knowledge about fire ventilation strategies in general and the specific tunnel fires in particular. Better knowledge is needed, which is also pointed at the context and conditions of the specific tunnels [1]. The investigation of the Oslofjord tunnel fire reviewed different reports related to safety and risk assessment made since the opening of the tunnel. A fire analysis from year 2000 recommended a performance based situation specific firefighting tactic regarding ventilation. NPRA's risk analysis from 2003 supports this issue [1].

The workshop participants agreed that the *interaction* between the NPRA's traffic control centre and the fire and rescue services' emergency centres are crucial for the outcome of the rescue operation. Today there is a lack of training and exercises involving these actors. At some emergency centres, it seems to be a problem that the operators do not know what to look for or what questions to ask when they communicate with the traffic control centre. Representatives from some fire and rescue services regarded the traffic control centres' competencies and knowledge as insufficient. This impression, however, varied across the country. In the eastern part of Norway, around the Oslo area, the traffic control centre was claimed to be highly competent.

After the fire in the Gudvanga tunnel, a medical scientist analysed the health situation for the victims trapped in smoke. The persons that walked out of the tunnel were exposed to major toxins and five of them were diagnosed with very serious injuries. They walked in 95 min. The event has raised concerns whether it is a good strategy to evacuate after the smoke has reached the road-users. A person struggling and using power to evacuate the tunnel consume significant more air, which might worsen the health condition. However, there is no scientific evidence on the survivability difference between evacuation strategies.

A representative from the fire and rescue service in the western part of Norway said he had been at the incident commander's operations centre on scene working as the leader of the fire and rescue operations. The leader of the health operation often asks if it is safe to send his or her staff into the building. This is a structural dilemma, because the physician is trained to assess smoke and toxin exposure upon humans, not the firefighter. The Police officer who is the Incident Commander has normally no idea in this respect. The workshop participant saw the situation as very problematic for the leader of the fire and rescue operations, being the expert on scene. He did not regard himself prepared for the expert role.

4.2.2. Insufficient capabilities

An interesting observation was that representatives from the eastern Norway were content with their tunnels, their collaboration with the NPRA and the safety systems, while representatives from west, middle and north were unsatisfied and expressed little confidence in the prevailing safety systems in general. The attitude was that the quality of the systems; detection, visualisation, ventilation, communication means, extinguishing equipment, etc. varied very much from region to region and tunnel to tunnel. A representative from the middle region of Norway said that they always experienced problems with the communication means, either between the traffic control centres at the NPRA and the dispatch centre at the fire department, or between the traffic control centre and the fire department in action. The representative from the transport industry also raised concerns about how their HGV-drivers should approach firefighting situations, balancing risk of injuries and the extinguishing possibilities in the early phases of the fire situation.

Several participants mentioned that the detection and alarm systems could be improved. Today HGV drivers and other road-users are very reluctant to stop and contact the traffic control centre using the SOS-telephones. Cell phones are preferred tools and hence it delays the response operations. The red lights outside the tunnels are easily misunderstood and not fit for purpose. Even the actors' respect of warnings had been experienced as very low, of which a situation was highlighted with a breakdown truck that disregarded the red lights, reopened the tunnel and reported to the traffic control centre. The traffic control centre applauded his work, which was completely against the procedures.

The AIBN criticised the predefined ventilation strategy in the Gudvanga tunnel fire claiming that both the fire department and the NPRA prioritized firefighting over rescue and evacuation [2]. AIBN recommended a situation-based strategy for the fire ventilation, although realising that such decisions will represent a challenge for the fire and rescue service. The AIBN had no solution on how to solve the performance based ventilation strategy besides addressing the need. A similar discussion at the workshop emphasized this dilemma, to which several participants had experienced that firefighting had been the main concern for the rescuers at the expense of the victims' urgent need for self-rescue. The professional fire and rescue services saw their roles to maintain rescue and evacuation, thus they could only rely on own resources to become in control of the situation. Most of the participants viewed the fire and rescue services as responsible for decisions regarding ventilation strategies in tunnel fires. The incident commander can choose other strategies than the one predefined in the emergency response plan. Discussions at the workshop concluded that the incident commander is considered the fire and rescue expert on scene; he or she is expected to make tough decisions that require some kind of expertise, but in reality, there is a lot they do not know. Several participants at the workshop expressed doubts concerning how realistic it is to expect such expertise in every Norwegian fire and rescue service considering the great diversity around the country. Questions were asked if it would be suitable to offer some regional or national support resources, some kind of expert network.

A representative from the fire and rescue service in the western part of Norway was concerned about the construction phase of tunnels, and possible fire situations that might occur. In the construction phase, the technical safety systems are preliminary and vital services might be omitted, such as firewater, ventilation or communication means. The interaction between coordinating parties in the construction phase was regarded a major challenge.

A representative from the fire and rescue service in the northern part of Norway had experienced the so-called "Goat cheese" fire in the Brattli tunnel. This fire lasted for four days, based on the first attempt to put out the fire failed due to not enough firewater and foam. According to the workshop participant the fire was almost extinguished. The fire clearly demonstrated the consequence of insufficient equipment. Another frustration forwarded by the representatives from north and west was their knowledge of ill-equipped tunnels, for example some of them lacking road barriers as a measure to stop traffic entering the tunnel in case of fires. In general, the concerns from many of the workshop participants were due to unfamiliarity with fighting tunnel fires. The formal general training activities at the academy have no or very little information and practices on tunnel fires.

5. Discussion

Nancy Leveson's [14] holistic model based on control and feedback mechanisms, and establishing constraints is interesting when we analyse the tunnel system actors' self-assessments of their knowledge and competencies. A pattern seen is that the members of the upper hierarchy level, representatives from the Directorates, viewed the situation significantly more positive than their system collaborators closer to the sharp end. Another tendency seen from the workshop was that the actors had a narrow perspective discussing their own activities, while the interactions horizontally and vertically in the tunnel system were very scarcely considered. An interesting observation is that Leveson [14] criticizes risk and vulnerability analyses for its simplifications and linear explanations of scenarios, while the workshop participants found risk and vulnerability analyses as alienating and complicating their picture of fire safety in tunnels. Introducing constraints, especially onto the interactions between various actors is a huge task, a paradigm shift, but it seems to be necessary in order to increase safety levels and general understanding of tunnel fires. Risk and uncertainty related to tunnel fire is difficult to grasp, and Leveson's presentations of the concepts are positivistic, which is impossible to defend ontologically [27]. Risk is an epistemological concept only; hence, reflections on methodologies, models, data, studies and learning activities are crucial for obtaining a foundation for improvement strategies.

The fire and rescue services have extensive tacit knowledge, which is unexploited and will remain so if experience transfer and teaching is still downgraded. The findings from the investigation reports after the two tunnel fires in 2011 and 2013 clearly show that the tunnel systems had substantial weaknesses related to safety constraints and feedback, and this way of thinking was absent from both the tunnel owners and the emergency response systems. Amongst a comprehensive set of analytical tools adapted to tunnel safety, risk analysis is promising, especially related to post accident phases. However, we observe analyses carried out mechanistically with the only purpose to document risk accept through results describing expected number of fatalities and serious injuries. This is the perspective of the authorities (EU and national authorities), and thus the objections raised by the workshop participants are reasonable and understandable. Such analyses are of no use to the fire and rescue services. Risk and vulnerability analysis is an approach to obtain system knowledge, raise objections and critics to the tunnel system (solutions), facilitate learning of important features of the system (in a Leveson perspective) and establish a foundation for the decisions made. Risk informed decisions would then be demystified and applied at various levels in the fire and rescue services [5]. This will encourage individual members of the tunnel safety system to develop their own risk images, which is an interesting prerequisite for learning and increasing competence levels as described by Sommer et al. [28].

The workshop participants called for more learning using arenas for exchanging experiences on tunnel safety. They also questioned how accident/incident reports and evaluations could contribute to learning. Making use of investigation reports and shared experiences can contribute to reflection, which is one of the components in the continuous learning process [28]. However, there have been very little concerns about how the various actors learn to approach and resolve tunnel incidents and fire scenarios. Strong voices at the workshop argued that today's education, training and follow up of fire and rescue personnel lack structure and planning. The leader education at the Norwegian Fire Academy were by some of the workshop participants regarded as insufficient, the amount of training and education related to tunnel safety seems not to be a prioritized area for the academy. The NPRA and the Directorate for Civil Protection offer a two days course at the Runehamar test tunnel twice a year. Some of the workshop participants recommended this course for inter alia understanding effects of fire ventilation. However, the training facilities are scarce and there are not enough capacities to cover the need for training in Norway. Furthermore, curricula and proper didactics are not developed. The workshop participants stressed the need to make a clear and consensual definition of what kind of scenarios the emergency response system is supposed to handle, in order to harmonize training activities. Considering the 13,000 employees of the fire departments working with prevention, mitigation and supervision tasks, the capacity and effort provided for increasing the competencies within tunnel fire safety is weak. The fire and rescue service is only one actor in the coordinated system of tunnel safety management. There is a need for a structural change to upgrade the competence level across units and organisations, changes that include arenas for comprehensive tunnel fire safety training.

Many road tunnels in Norway are complex structures containing traffic flows of varying high-energy substances in an uncontrollable environment. A huge number of subsystems and units might interact in unpredictable ways. Some of the tunnels could be characterised as tightly coupled with complex interactions [22]. We ask ourselves; are these tunnels properly governed in contrast to other complex systems? After the devastating Piper Alpha accident in 1988, the UK offshore oil and gas installations have been subjected to "Safety Case" regulations based on the Norwegian performance based regulation ("Lex Ognedal"). We claim that many of the Norwegian road tunnels represent larger complexity and worse potential consequences in case of fires than for example unmanned offshore oil and gas facilities. Both systems are remotely operated, which makes it plausible to discuss Safety Case requirements also for road tunnels. There exists an extensive amount of scientific literature across various industries that support this regulatory approach [26,29,6–8]. Introducing Safety Case will also clarify the NPRA's various roles, and through this establish the municipality fire and rescue service's responsibility and sanctioning ability as the supervisory agent. Furthermore, the fire and rescue services will be involved in the Safety Case and holistically assess the performance of the tunnel system as such.

6. Conclusions

This study has revealed tunnel fire safety concerns related to the Norwegian emergency response personnel's state of competence both in the pre- and post-accidental phases. Some of the uncertainties relate to:

- Little knowledge about traffic conditions, road-user behaviour and contents of goods travelling through various complex tunnels.
- Understanding the purpose, concepts, contents and benefits using risk and vulnerability analysis.
- Comprehension of ventilation strategies, and the vast number of experts in the field recommending various solutions.
- Situation awareness when meeting a tunnel with smoke coming out.
- The self-rescue principle seen in the context of crisis response.
- Interaction between parties that need to communicate.

Some of the insufficient capabilities relate to:

- Supervisory tools and sanctioning abilities of the fire and rescue services in their inspection activities and communication with tunnel owners.
- Dimensioning practices of tunnel designs and use of risk and performance analyses.
- Huge variation between technical safety systems across the country, leaving some fire and rescue services with few opportunities in the fire response.
- Knowledge and expertise in fighting tunnel fires.

The current practices of managing tunnel fire safety are unclear and fragmented, and the state of knowledge regarding pre-accidental measures and post-accidental responses are weak. The future will bring even more complex road tunnels, also subsea-crossings, which challenge all parties: road owners, road users, vehicle producers, emergency responders and authorities. We need facilities for tunnel safety training that can complement existing facilities and provide new knowledge based on systems engineering.

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