Emergency Preparedness for Tunnel Fires

A Systems-oriented Approach

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ABSTRACT

Road tunnels are important elements in the Norwegian communication infrastructure. According to the Norwegian Public Roads Administration (NPRA) *"the risk is low, but the accident potential is high"*. Hence, efficient emergency response is key to prevent major injuries and losses in tunnel fires. Our general concern in this paper is to what degree we are prepared, and by which means we can be prepared for a major fire in a single tube road tunnel. Successful emergency response to tunnel fires is dependent on many actors collaborating under serious time constraints. Safety becomes a matter of maintaining the critical processes necessary to keep the system in a safe state. Efficient decision-making in situations of major uncertainty is essential to achieve safety goals. This essentially means that efficient emergency preparedness to road tunnels is a matter that needs resolving in the design, construction and normal operation phases. To achieve high-performance emergency preparedness to tunnel fires, there is a need for radical changes to designing and operating tunnels. In this paper, we claim 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.

BACKGROUND

Road tunnels are important elements in the Norwegian communication infrastructure. Some tunnels are urban, complex traffic machines facilitating heavy traffic. A significant number of tunnels are low standard and low traffic tunnels, located miles away from poorly equipped voluntary fire departments. Tunnels imply potentials for major accidents, calling for professional emergency response arrangements. Every year Norway experience about 20 fires in its 1150 road tunnels. The Norwegian Public Roads Administration (NPRA) bases risk on the historical frequency of fatal traffic accidents, often claiming; *"the risk is low, but the accident potential is high"*. It is true that Norway has not yet experienced many deaths in road tunnel fires. However, there have been 5-6 severe incidents the past decade, to which it is easy to portray disastrous scenarios exposing many people to a deadly fire.

Emergency preapredness

Emergency preparedness are 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 [1].

November 2016, the NPRA issued a new version of Handbook N500 Road Tunnels [2]. This version introduces the concept of emergency preparedness as a part of the safety management of Norwegian road tunnels. An emergency preparedness analysis are now required for tunnels > 1,000 meters. The emergency preparedness analysis must cover the phases from *alert*, *mobilization*, *rescue*, *evacuation* and *normalization*. There is, however, no mentioning of the important phases of *detection* and *combat*, which are natural parts of an emergency preparedness analysis [1].

Although it is required that road tunnels are to be designed based on risk assessments and emergency preparedness analyses, a major problem is that none has described acceptable risk levels or specific requirements to emergency preparedness. As a quality assurance measure, N500 require 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 selection of methods for risk and preparedness analyses depends upon the scope of the analyses and available data, the practice impose major competency requirements on those who shall approve the methodological design.

Performance - a systemic issue

In this paper, we adopt our proposed framework [3] for assessing emergency response strategies to fire in a single tube road tunnel. Our study holds a Norwegian perspective concerning road tunnel standard, safety regulations, dimensioning of emergency response and its organization, climate and other frame conditions. We have selected a Norwegian single-tube road tunnel as an object for case studies.

When the performance of the evacuation system is part of the risk and preparedness analysis, the development of dimensioning events is crucial. This includes specifying the competency and state of the road-users, the number of road-users involved, fire scenario and emergency response actions. Simulating the fire scenarios is an important part of the analyses, which will lead to exposure of the road-users and demonstrate that, e.g. emergency shelters need to be installed and used.

Our general concern is to what degree we are prepared, and by which means we can be prepared for a major fire in a single tube road tunnel. Are Norwegian tunnels designed and equipped to allow for efficient self-evacuation? Are responsibilities related to emergency preparedness sufficiently clarified? Are Norwegian tunnel-users familiar with emergency response strategies? Are there weaknesses in the operational safety management organization? Finally, is the predominant Norwegian strategy for emergency response to fires in single tube road tunnels appropriate to facilitate the best chances of saving lives?

We discuss the application of systems thinking for emergency preparedness analyses for road tunnels, which emphasizes consequences and associated uncertainties. Systems thinking may serve as a complement to risk-based thinking. The systems-oriented approach emphasizes the description of the system, the development of dimensioning scenarios and identification of the necessary safety constraints in order to keep the system in a safe state. So instead of looking for probabilities, uncertainties and adverse events we look for road-users' and emergency services' performances to ensure that safety is controlled for the tunnel system.

We address the development of safety constraints from the use of fire investigations and we discuss 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 tunnel's emergency preparedness system into practical administration work.

PROBLEM FORMULATION

According to Leveson [4], accidents are products of inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system. Safety is a control problem. Accidents may occur due to 1) failure to identify hazards and safety constraints, 2) failure to maintain the safety constraints, 3) inconsistency between process behavior and process models, and 4) lack of system state feedback in order to update process models.

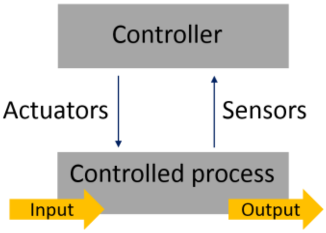

Figure 1. General control loop

The control actions must take place in a complex and dynamic socio-technical system. A fire situation in a road tunnel involves many actors, whose individual actions, and interaction with others, will determine the outcome of the incident. Leveson claims that accidents occur because the controller has not enforced the safety constraints, or that appropriate control actions has not been followed. In a previous paper [3] we have outlined a framework for fire safety design from a systems theoretic perspective.

When a fire occurs in a road tunnel, the predominant strategy is to start the longitudinal fire ventilation. Wind direction is usually predetermined based on the location of the most resourceful local fire department. Wind direction from this location allows the fire department to enter the tunnel with the wind in their back. This allows for safe advancing towards the fire and improves conditions for effective firefighting. We question this strategy for single tube road tunnels. Our main concern has been to study the consequences of unconditionally prioritizing safe firefighting conditions over other concerns, such as life safety conditions for road-users within the tunnel. This kind of ventilation management has the potential of exposing many people to harmful conditions, and thereby worsening the situation for the involved.

MAJOR NORWEGIAN TUNNEL FIRES

This section include findings from investigations after some major Norwegian tunnel fires during the past decade. These narratives serves as a reminder of what fire scenarios we might expect in the future and illuminate variations in critical factors. Hence, it implies what loads we may expect a fire to impose on *the emergency response system*, including the tunnel 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). None was killed in the presented fires, but international tunnel fires, such as the Mont Blanc, the St.Gotthard and the Tauern fires remind us on the extent and devastating impact. However, for the Norwegian fires it is easy to portray alternative circumstances that may have led to several fatalities.

Oslofjord 1 (March 29, 2011)

A fire started in a Polish lorry loaded with 30 tons of paper rolls. The fire occurred near the low point of the tunnel, and from the video camera, the operator saw flames coming out from one of the lorry's wheel areas. The driver reported that he tried to put out the fire using extinguishers placed in the tunnel, but he did not manage to control the fire. In accordance with the emergency preparedness plan, longitudinal fire ventilation was activated, all lights were turned on and the tunnel was closed with red lights and gates. After the fire, it was reported that several vehicles passed the fire and that several vehicles ignored the red signal and gate/barrier. Four persons was treated in hospital while medical personnel on site checked two persons for injuries.

Oslofjord 2 (June 23, 2011)

The fire started in a Polish lorry during the uphill drive from the low point towards Drøbak. The fire started in the vehicle's engine. The driver tried to put out the fire, but was not able to control it, and had to evacuate by foot 1.7 km towards Drøbak. The lorry was carrying about 23 tons of waste paper, and the heat release rate is calculated to about 70-90 MW. In accordance with the emergency preparedness plan, longitudinal fire ventilation was activated with a pre-determined direction from Drøbak to Røyken (from East to West). Consequently, 5.5 km of the tunnel was filled with smoke. Immediately upon arrival, the fire department started extinguishing the fire. After about 45 minutes and spending 20-30 m^3 water, the fire was extinguished. When the fire started, 34 persons was in the tunnel. 25 managed to evacuate without assistance. Emergency personnel assisted 9 persons, of which 8 had sought refuge in SOS stations and later managed to enter the space between the concrete tunnel lining and the rock. 32 people were treated in hospital.

Gudvanga 1 (August 5, 2013)

A fire started in a Polish lorry. The lorry had unloaded in Bergen and was not carrying any cargo on its way towards Malmö. After driving some 6 km into the 11.4 km Gudvanga tunnel, the driver became aware that he lost engine power. He stopped the vehicle after continuing 2 km further into the tunnel. Consequently, the vehicle was located about 3.5 km from the Aurland (east) portal. The fire started in the engine and the driver tried to put it out using his 6 kg fire extinguisher from the vehicle. This was not sufficient and the fire grew rapidly until it flashed over after about 20 minutes. Calculations show that the heat release rate was in the area 25-45 MW. In accordance with the emergency preparedness plan, longitudinal fire ventilation was activated with a pre-determined direction from Aurland to Gudvangen. Consequently, smoke filled 8.5 km of the tunnel. Smoke spread obstructed 15 vehicles and 67 people that the fire department later rescued. 28 people was treated in hospital, from which 5 and 23 was classified with *very serious* and *serious* injuries respectively.

Gudvanga 2 (August 11, 2015)

A fire started in a tourist bus containing 32 Chinese passengers driving from Flåm towards Gudvangen. The bus driver had noticed a loss of engine power while driving through the preceding Flenja tunnel, but continued into the Gudvanga tunnel as he retrieved the engine power. However, 360 meters into the Gudvanga tunnel, he saw flames in his left side mirror. The automatic fire extinguishing system in the bus' engine compartment activated and signals showed up on the dashboard. The driver evacuated passengers, and had them placed into a passing empty van. The van transported the passengers to safety on the Gudvanga side. The bus driver tried to put out the fire using a fire extinguisher, but the fire continued and grew to an estimated heat release rate of 30 MW. He then called the emergency number, which again activated triple alert. Tunnel operators (VTS) closed the tunnels using red signals and gates. The fire department requested VTS to await activation of the longitudinal fire ventilation, but ventilation activated automatically towards Gudvangen when the bus driver removed a fire extinguisher from the tunnel wall. This led to a change in the initial ventilation direction and to transport of smoke 11 km towards Gudvangen. 19 vehicles managed to turn around and drive out of the tunnel. Five people in three vehicles was trapped. Instructed by emergency responders over mobile phones, none of the five left their vehicles. After receiving information about trapped people, the emergency responders ordered a change in the ventilation direction. The five people in the tunnel was found by smoke divers from Voss fire department after ca. 1.5 hours, and was transported to hospital for treatment of smoke injuries.

Skatestraum (July 15, 2015)

On July 15, 2015, a Norwegian heavy goods vehicle that consisted of a truck and trailer, loaded with 19,000 and 16,500 liters of petrol respectively, drove through the Skatestraum tunnel from Måløy towards Florø. About 450 meters after starting the uphill drive from the lowest point of the tunnel, the trailer broke loose from the truck and the front right-hand corner hit the tunnel wall. The impact made a hole in the front tank chamber and the petrol it contained ran out. The tunnel operators received a message that petrol was leaking and closed the tunnel. The petrol ran towards the low point, and eventually caught fire. The fire then spread upwards from the low point to the east portal, a distance of about 900 meters. Calculations show that the heat release rate may have been above 400 MW during the initial phase of the fire, when both running petrol and petrol in the trailer burned. It is estimated that the heat release rate was above 200 MW while only the petrol in the trailer burned. The ceiling temperature above the fire was calculated to about 1350 °C. When the fire started there were four cars and a camping vehicle in the tunnel, including 17 people. All the vehicles was behind the tanker, driving in the same direction. The first car turned around when the driver witnessed the trailer colliding with the tunnel wall. He was also able to stop and turn a second car, who drove out of the tunnel. The third car stopped some distance behind the trailer due to a flat tire. A camping vehicle then passed this third car and drove up to the trailer. When the camping vehicle was about 5-10 meters from the trailer, they heard a bang and the trailer caught fire. The driver of the camping vehicle backed away from the trailer towards the low point, catching up with two persons from the third car who had started running when they saw the fire starting. The two persons was picked up by the camping vehicle and they backed some distance up the other side of the low point, turned the vehicle and drove out. While backing down the tunnel they saw flames coming up the sides of their vehicle.

Oslofjord 3 (May 5, 2017)

In 2017 a fire similar to the severe *Oslofjord 2-fire* occurred. A lorry loaded with toilet paper started burning due to engine failure. During the tunnel closing operation, several vehicles, including two lorries, drove into the tunnel. The two lorries drove up to the burning vehicle and was not able to turn. The fire escalated quickly, and the fire service barely managed to prevent fire spread to the two lorries located behind the burning vehicle. After the Oslofjord 2-fire, evacuation shelters were installed in the tunnel. During the Oslofjord 3-fire, two persons evacuated their vehicles and found shelter in one of these rooms. The two persons was later picked up by the fire service.

OBSERVATIONS FROM TUNNEL FIRES

Based on previous analyses of Norwegian events we think that safety should be improved based on various characteristics with the tunnel designs:

- It takes too long time before road-users realize dangerous situations in tunnels and prepare for self-evacuation.
- The organizing of self-evacuation is arbitrary and to a very little extent adapted for the road-users' needs.
- The road-users do not possess knowledge of tunnel fires, e.g. illustrated by keeping little distance to the vehicle in front and postponing evacuation actions.
- Ventilation strategies do not correspond with fire, situational and emergency response scenarios.
- Fire extinguishing equipment is inappropriate to match relevant fire scenarios.
- The buyer of transport services, transport salesmen, forwarding agents, transport companies and drivers of HGVs containing large amount of energy has been very little considered and scrutinized 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.
- Procedure driven or knowledge based fire and rescue work must be balanced. No one seems to define what is a good balance.
- Easy accessed information about Norwegian road tunnels and fire protection strategies is lacking.
- The individual victims from fires' post traumas and stresses are underrated.

Knowledge about the contents of goods travelling through Norwegian tunnels is scarce. This is especially true with regard to the potential for exposure to toxic substances in serious releases and combustions. The tunnels are sociotechnical systems not very easily predicted in case of future accidental events. For the 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 [5].

SAFETY – A CONTROL ISSUE

Based on the scenarios described in the previous section, this section exemplifies a set of safety constraints to enforce to keep the tunnel in a safe state. Safety constraints are logical developments from the Zero Vision strategy, politically enforced in Norway September 29, 2000. We assume that there exist a set of functional requirements to the tunnel design, for example:

- The tunnel design shall ensure safe behavior by being logical and easy to understand.
- The tunnel shall invite and guide to correct speed and stimulate to awareness.
- Alarm shall be given in a way that ensures effective mobilizing of all relevant emergency services and measures.

Based on a common understanding of overall functional requirements it is relevant to discuss constraints. In this example, we use the narratives to clarify a set of constraints.

The narratives

During the past three decades there have been several major events/crises that have struck road tunnels. Most of them are thoroughly investigated. The investigations contribute with interesting features relevant for all tunnel designs in Norway. Furthermore, the NPRA also investigates all fatal accidents in their infrastructure including tunnels, which provide useful information. Last, but not least, the traffic management centers in every region have records of deviations and events regarding the traffic in all tunnels in its region. We exemplify safety constraints by referencing the above incidents, but advocate the development of constraints on a broad material, in which most of them will be standardized but some also tailor-made for the specific tunnel.

Safety constraints

Developing safety constraints follows a systematic process involving these 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 of safe operation. The validity of the scenarios is assessed by coherence principles, see Bjelland et al [3], which we will not elaborate 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. Derivation of safety constraints are based both on the hazard identification process directly, and the scenario analyses.

The safety constraints should comply with a set of requirements:

1. *Observable*, they must be clearly defined and open for access when needed.
2. *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 of knowing the status of the controlled process. Hence, the constraint must *allow appropriate feedback to the controller*.
4. *Evenly distributed* amongst actors involved with safety management.
5. *Correspond to an available controller*. If there is no controller to enhance the constraint, the constraint is meaningless.

The following are examples of relevant safety constraints upon the evacuation system that need enforcement in order to keep a tunnel in a safe state, based on the role of the controller:

- Road-users must…
  - know in what tunnel they are.
  - know where they are in the tunnel, relative to the threat and to the means of egress.
  - have adequate knowledge about the evacuation strategy of the specific tunnel.
  - have knowledge about fire spread mechanisms (keep distance to vehicle in front of you).
  - have adequate knowledge about how to extinguish a fire.
- Emergency responders must…
  - know the location of the fire.
  - know if and where any road-users are in the tunnel.
  - are aware and trained for the fire safety strategy (information, ventilation, evacuation, etc) of the specific tunnel (ex: In Gudvanga 2 the ventilation strategy seemed to be a surprise for the emergency response).
- Tunnel owners must …
  - ensure that the fire extinguishing equipment in the tunnel corresponds to dimensioning scenarios and road-users' capabilities (Ex: none of the drivers succeeded in putting out the fire).
  - ensure that the fire ventilation system corresponds to the traffic in a road tunnel, which should not lead to fire scenarios exceeding the ventilation capacity of (Ex: Skatestraum fire).
  - ensure the technical safety systems has uninterrupted power supply during the fire (ventilation, lights, information systems, communication systems) (Ex: Gudvanga 1)

Sensor, controller, actuator – scenario analyses

We state that safety is a control problem. A control structure (or a controller) is thus essential in order to obtain safety. If there is no controller, there cannot be safety. The self-rescue principle is an important design presumption for Norwegian road tunnels. Following this principle, the tunnel design is in accordance 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.

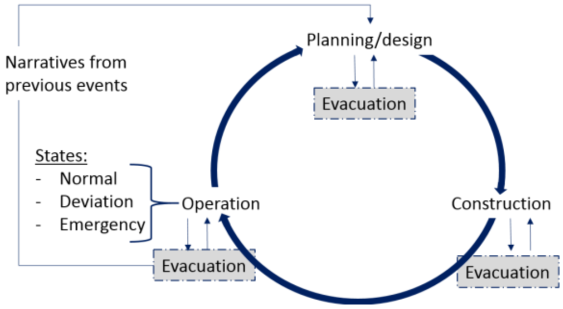

Figure 2. Evacuation as a controlled process through planning, construction and operation

If safety is the system's ability to prevent injuries and losses, the design of the system becomes a major issue. Control and feedback are major issues in systems theory. Feedback to the controller is important. Situations of emergency develop quickly. Decision-making in response to avoid injuries and losses is dependent on high quality information. The major idea is that the controller is updated on the process that he/she/it is controlling.

The constraint; Road users must have adequate knowledge about how to extinguish a fire; meet the requirements, if we describe adequate knowledge. The constraint is directed at the population of HGV-drivers, and the controllers are the road authorities, training schools (drivers shall refresh competence in intervals of five years) and transport company. The responsibility of the control-function needs thorough consideration, but we neglect this issue. Sensor activities are reports from training, exercises and surveys, to which the controller must apply the algorithm (assessment) to when critical level is crossed (portion of drivers not holding a certain standard, given the design of the specific tunnel).

Control enforcement on the process require actuators. In the example above, actuators could be relevant on several levels. Of course the transport company is responsible for maintaining mandatory competencies, which include fire extinguishing in tunnels. Additional training is an obvious measure. For the drivers schools changes to curriculum, didactics and testing might be relevant. Finally, for the road authorities strengthening the regulation might be necessary.

In tunnels, feedback from the various processes require sensors. Norwegian road tunnels (at least the single-tube rural tunnels) are scarcely equipped with sensor technology. Adequate feedback from the process (situation of emergency) 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 our narratives from Oslofjord 1 and 3, we see that vehicles enter the tunnel against red lights and closing gates. Similar findings are reported e.g. in the Mt. Blanc tunnel fire in 1999 [6]. This indicate poor feedback from the incident and/or inadequate control actions from 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 strengthen the evacuation process control. People are reluctant to initiate immediate evacuation in early stages of fire emergencies, but also suggest that information is key to compensate indecisive behavior.

Assessment of coherence

Coherence analysis shall ensure that the scenarios and related constraints are validated. Stakeholders must be involved in the coherence analysis, which contains narratives based on various loadings put on the tunnel system, where explanations are sought regarding why devastating developments are avoided. Justifications of assumptions, constraints and related coherences are the major concern of the analysis, but a thorough presentation of the use of coherence principles is not part of the scope of this paper.

DISCUSSION

Road tunnel fires can be challenging and cause health risks to the firefighters. The guidelines for smoke and chemical dredging places relatively large restrictions on advancing towards tunnel fires. Advancing towards a tunnel fire should not be conducted against the direction of the ventilation. A tank wagon should accompany the fire fighters where there are no fixed water outlets in the tunnel. In addition, it is essential to establish communication between fire fighters entering the tunnel and the command center on the outside. Once the basic prerequisites are satisfied (ventilation, adequate water supply and communication), an assessment of the severity of the incident must also be made. In cases where the severity is unknown, the fire service should be careful when entering the tunnel.

In 2015 we did a workshop challenging fire and rescue services across Norway on their knowledge and capabilities to respond to major tunnel fires [7]. The workshop revealed huge variations amongst various fire departments responsible for complex tunnels. For example, imagine a rural sub-sea tunnel, which is not equipped with either fire ventilation, water outlets, video surveillance, or the national emergency communication system. Still, first responders might have a relaxed attitude towards the guidelines for smoke and chemical dredging. In case of a tunnel fire, the procedure could include backing the fire engine with four-five firefighters towards the fire, even against the ventilation direction. We know of a specific traffic accident in a subsea tunnel, to which the fire department advanced towards the fire without establishing a communication gateway. This was not a fire, but how could they evaluate the scenario without video surveillance?

Njå and Svela [7] suggest that tunnels should be subjected to "Safety Case" regulations, to which the tunnel owner in close cooperation with the rescue services need to demonstrate sufficient 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 from the local fire service needs clarification, and the tunnel must be equipped accordingly. Our view is that the society expect the fire department to push limits to fight a fire in the tunnel and rescue people. The fire department also seem to place high expectations on themselves. The fire department's actions in the Gudvanga 1 fire corroborates this. In many municipalities, a local voluntary fire department is responsible for the emergency preparedness and response for major road tunnels. The emergency preparedness analysis should recognize the emergency responders' limitations and design the tunnel accordingly. However, it could be questioned whether this is practice today. We question both the local voluntary fire department's competency with regard to understand their own limitations and the current emergency preparedness analyses' ability to identify weaknesses and compensate by safety measures on tunnel design. In other words, the tunnel design does not match the emergency response capacity, which may lead to an emergency response that do not match the situation in the tunnel. This is a clear example of safety constraints being violated.

CONCLUSION

Successful emergency response to tunnel fires is dependent on many actors collaborating towards avoiding injuries and losses. When a fire incident occur 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 approaches. Efficient decision-making in situations of major uncertainty is essential to achieve safety goals. This essentially mean that efficient emergency preparedness to road tunnels is a matter that needs resolving in the design, construction and normal operation phases. Emergency preparedness analyses are required in the design phase by Norwegian legislation for tunnels > 1 000 m. Guidance and functional requirements are lacking. The combination of a prescriptive-based regulation regime and strong traditions and expectations to 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 to tunnel fires, there is a need for radical changes to designing and operating tunnels. Management should shift from compliance-based to functionally based, including clear performance requirements to 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-user's and local emergency response teams' different capabilities. In this paper, we claim 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.

REFERENCES

[1] O. Njå, *Approach for assessing the performance of emergency response arrangements*. Stavanger, Norway:

Aalborg University/Stavanger University College, 1998, p. 1 b. (flere pag.).

[2] (2016). *Håndbok N500 Vegtunneler [Handbook N500 Road Tunnels]*.

[3] H. Bjelland, O. Njå, A. W. Heskestad, and G. S. Braut, "The Concepts of Safety Level and Safety Margin: Framework for Fire Safety Design of Novel Buildings," (in English), *Fire Technology,* pp. 1-33, 2014/04/09 2014.

[4] N. Leveson, *Engineering a safer world: systems thinking applied to safety*. Cambridge, Mass.: The MIT Press, 2011, pp. XX, 534 s., ill.

[5] O. Njå, "Self evacuation from fires in long subsea road tunnels: the case of the Oslofjord tunnel fire in 2011," presented at the 7th International Symposium on Tunnel Safety and Security, Montreal, Canada, 16 - 18th March, 2016.

[6] J. Shields, "Human behaviour in tunnel fires," in *The handbook of tunnel fire safety*, A. N. Beard and R. Carvel, Eds. London: Thomas Telford, 2005.

[7] O. Njå and M. Svela, "A review of competencies in tunnel fire response seen from the first responders' perspectives," *Fire Safety Journal,* 2017/05/20/ 2017.