Applying Systems Theory to Increase Competence in Tunnel Fire Safety – Focusing on the Fire and Rescue Services

Gabriela Bjørnsen

Rogaland Fire Department & University of Stavanger, Norway. E-mail: gabriela.bjornsen@rogbr.no

Ove Njå

University of Stavanger, Norway. E-mail: ove.njaa@uis.no

ABSTRACT: Several publications have raised concerns over the state of knowledge and competence in tunnel fire safety amongst fire and rescue personnel. Although fires in road tunnels are not common phenomena, the fire and rescue services still have to cope with such incidents. In order to perform an effective emergency response in the event of fires or other emergencies it is essential that the fire and rescue personnel possess necessary knowledge and skills. The responsibility to develop knowledge and competence amongst fire and rescue personnel is shared by a large number of actors at several hierarchical levels. The diversity of actors and organizations, as well as the interactions between them, makes the fire and rescue system a complex sociotechnical system. The Norwegian emergency response systems are partly designed on self-regulation principles, which encourage creative solutions. However, it seems that the frame conditions for developing optimal learning systems are not in place. So far, no agency seems to be able to establish recognized constraints that enables the involved actors to define their own competence levels. A set of safety constraints to learning processes is proposed to enable control and improvement of tunnel fire safety and rescue competencies.

Keywords: *Tunnel fire safety, knowledge and competence, fire and rescue services, fire and rescue personnel, emergency response.*

1. Introduction

Road tunnels represent a significant share of the Norwegian road network. As of today, Norway has more than 1100 road tunnels that together constitute 1134 kilometers. Among these, 148 are longer than 2 kilometers and 35 are subsea tunnels with steep slopes (>5%). Reports have shown that road tunnels have a lower frequency of incidents per vehicle/km than open roads (Nævestad and Meyer, 2012; Nævestad et al., 2016). However, the severity of incidents in tunnels, especially fires, may lead to critical consequences for the tunnel users, the tunnel infrastructure and the environment. The Oslofjord tunnel fires in 2011 and 2017, the Gudvanga tunnel fires in 2013 and 2015 and the Skatestraum tunnel fire in 2015 have enhanced the Norwegian society's concerns regarding the safety level of the tunnels. As a result, the Norwegian authorities have critically investigated those incidents. Several of the publications have pointed out that there is an urgent need to improve the safety level in tunnels and the capacity of the emergency services to cope with incidents in order to prevent and mitigate the consequences of accidents and fires (AIBN, 2013/05; 2015/02; 2016/03; 2016/05; 2018/04).

Currently, two of the world's longest subsea tunnels are being erected in Rogaland, both with a significant longitudinal gradient. Changes to the road network, changes in the heavy goods vehicles and driver behaviors, and changes in traffic patterns generate new challenges for the fire and rescue services' emergency response operations. According to Njå and Svela (2018), the current situation in tunnel fire safety is unclear and fragmented. The state of knowledge regarding prevention measures and emergency response strategies appears to be weak.

Fires in road tunnels are some of the most challenging and complex tasks in which the fire and rescue services are involved. Long bi-directional single tube tunnels with steep slopes and no other exits beside the tunnel portals, put great demands on the emergency response operations. Although fires in road tunnels are not common phenomena, the fire and rescue services will have to cope with such incidents. PIARC publications acknowledge training and exercises as essential for the emergency response services' preparations for real events and maintaining their capacity to cope with fires and incidents in tunnels (PIARC, 2012a). It is therefore crucial that the personnel possess comprehensive knowledge of the tunnel's equipment and its contingency plans.

The Norwegian emergency response systems are designed partly on self-regulation principles, which encourage creative solutions. Norwegian authorities must therefore facilitate and promote conditions that aim to develop optimal learning systems. So far, no agency seems to be able to establish recognized constraints that enables the involved actors to define their own competence

Proceedings of the 29th European Safety and Reliability Conference.
Edited by Michael Beer and Enrico Zio

ISBN: 981-973-0000-00-0 :: doi: 10.3850/981-973-0000-00-0 esrel2019-paper

levels. In this paper, we consider the *Norwegian tunnel fire safety learning system* for fire and rescue personnel as a complex socio-technical system. By using a systems theory approach to safety, we discuss how this system may be modelled in order to achieve increased competence. Our starting point is that the existing regulatory framework has not established appropriate constraints for the tunnel fire safety learning system.

2. Risk Assessments for Road Tunnels

In the aftermath of the major tunnel fires in Europe the European Commission developed the Directive 2004/54/EC that sets the minimum safety requirements for tunnels on the Trans-European Network (TERN) (EU, 2004). The directive requires that risk analysis shall be carried out for tunnels with special characteristics. A purpose with the risk analysis is to form a basis for decision-making for the tunnel owners, inform authorities, as well as to assist emergency response services to form their contingency plans and determine an appropriate level of competence. Taking into account that the directive does not specify an explicit method to conduct risk assessments for tunnels, a large number of assessments have been conducted, most of them based on Quantitative Risk Analysis (QRA) (PIARC, 2008). Such approaches are ideally systematic assessments of the risks identified in a specific tunnel by taking into account local characteristics and factors, their interactions and possible outcomes of incidents (PIARC, 2012b). A main challenge when using quantitative methods is that the available data may not be sufficient. Thus, the parameters included in the analysis may represent a simplification of the real state of the system. There are many sources of uncertainties involved in risk analyses (Njå et al., 2017). It is difficult to predict exactly how a tunnel fire will develop due to several specific circumstances, such as the amount of heavy goods vehicles and their load, the number of road users, the capability of the emergency response services to cope with the fire.

Despite QRA contributions to improve and optimize the safety level of road tunnels, it has been argued that QRA methods alone should not form the basis of safety related decision-making (Kazaras & Kirytopoulos, 2013, Time & Njå, 2017). Since the implementation of the directive, the Norwegian Public Roads Administration (NPRA) has conducted a large number of risk analyses. An evaluation of the risk assessment techniques adopted by the NPRA show that risk analysis are often used to legitimize choices and solutions of the tunnel systems (Njå et al., 2013). The analysis are considered confirmations of the measures preferred, rather than an input into the decision-making process. Bjelland and Aven (2013) have also conducted a review of the risk assessment method of the Rogfast tunnel. The authors stresses that considerable uncertainties and risks are neglected in the risk assessment process, and that there is a discrepancy between the existence of uncertainties and the way they are being considered and handled. A way of dealing with the complexity is to apply systems theory

3. System Theory Applied to Tunnel Fire Safety Learning System

Nancy Leveson (2011) developed her approach to safety management partly based on a critical stance towards traditional risk management approaches. Complex socio-technical systems, she claims, represent more than an accumulation of technological artefacts. Such systems may be considered as an aggregation of structures, management, procedures, and organizational culture. System theory focuses on systems as a whole and not on the components taken separately. The fire and rescue services represent a system that is continuously affected by interactions between its components and elements in the surrounding environment. The responsibility to develop knowledge and competence amongst fire and rescue personnel is shared by a large number of actors at several hierarchical levels. The diversity of actors and organizations, as well as the interactions between them, gives the fire and rescue system the properties of a complex socio-technical system.

According to Leveson most accident and incident analyzes focus mainly on understanding failures in events that have led to the losses. Thus, analyzing accidents as a chain of events may cause limitations when trying to understand and learn from the causal factors of an accident (Leveson, 2011; Rasmussen, 1997). In the complex systems in societies, accidents arise in the interactions between the system components, which all may satisfy their individual requirements. Rasmussen claims that such environments require studies of the vertical interaction between the different levels of a system, as well as the mechanisms generating behavior in the dynamic context.

3.1. The STAMP approach

System Theoretic Accident Model and Processes (STAMP) is based on two fundamental pairs of ideas; (1) emergence and hierarchy, and (2) communication and control. An underlying concept is that accidents occur because of inadequate control actions rather than failure in event chains. Thus, some properties of a system can only be handled in their entire context. Safety becomes an emergent property of systems that can be achieved through enforcement of constraints, and therefore only possible to determine in the context of the whole system. The approach emphasizes that unless constraints of safe behavior are not enforced, individuals will explore the boundaries of established practice and occasionally cross the limits of safe practice, which may lead to accidents. Leveson claims that; *… enforcing safety constraints on system behavior requires that the information needed for decision making is available to the right people at the right time* (p.307).

The tunnel fire safety learning system has special characteristics affecting the personnel's ability to prevent and cope with tunnel fires. The characteristics are reflected through laws, regulations, educational curricula, learning goals and plans, learning and training activities, procedures, as well as the personnel's qualifications. It is represented at different levels in the fire safety and rescue system hierarchy. Based on STAMP, behavioral constraints must be identified and implemented at the different levels in the system. Further on, the control loops between the system's hierarchical levels are intended to provide the necessary information to impose appropriate safety constraints, as well as provide feedback about the efficacy of the existing constraints. Learning represents an essential part within the systems theory approach.

4. Learning Perspectives

Researchers have found it difficult to accept a single definition able to capture all aspects of the learning concept (Hergenhahn & Olson, 2001). Braut and Njå (2013) state that in recent years it is possible to identify a change from understanding learning as an acquisition of individual knowledge and skills, towards understanding learning as participation and involvement in social systems. Some researchers have shown that those two approaches are complementing each other, and must therefore be considered when trying to capture and understand how individuals learn (Illeris, 2007; 2011, Sommer et al., 2013).

4.1. Learning in emergency response work

Fire and rescue personnel acquire much of their knowledge and skills through practice and experiences. Experiential learning theory emphasize that learning is a process, which produces knowledge through transformation of experience. It represents a holistic integrative perspective on learning combining experience, perception, cognition and behavior (Kolb, 1984). Kolb's experiential learning cycle comprise four stages that a learner goes through in the learning process: concrete experience, reflective observation, abstract conceptualization, and active experimentation. A person who wishes to learn necessitates the ability to engage in all the four stages. Learning through workplace participation makes also strong contributions for fire and rescue personnel's ongoing development of knowledge and competence. According to Gherardi et al. (1998), this approach does not pay particular attention to the cognitive processes inside the individual mind, but emphasizes the social structures and concepts of a learning situation. Learning situations are embedded in communities of practice, controlled by history, norms, tools, and traditions of practice (Lave & Wegener, 1991).

Sommer et al.'s (2013) learning model, depicted in Figure 1 sees learning as a continuous and dynamic process, where new knowledge and skills are developed based on previous knowledge and experiences in both formal and informal learning settings.

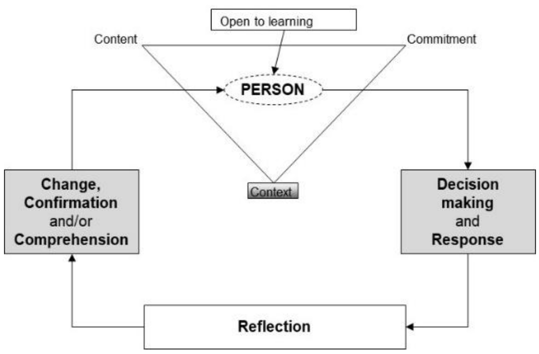

Fig. 1. Learning model based on Sommer et al. (2013)

The starting point to understand learning is the individual, placed within the elements of *content, context* and *commitment*. A prerequisite for individuals to learn is that they are open and motivated, as well as a wish to acquire new knowledge and skills. The way individuals involve themselves in learning activities will strongly influence what is being learnt, and if learning occurs at all. In order to improve performances, the practical and theoretical contents of learning must be experienced as relevant for the learners. Contextual factors such as social climate, relationships, trust and learning environment will also strongly influence individuals' possibility to learn.

Decision-making and *response* correspond to what individuals do in order to deal with emergency situations (Sommer et al., 2013). During emergencies or training exercises the fire and rescue personnel must be able consider relevant situational cues when making decisions and choosing relevant actions. The result of these decisions form the individuals' behavior and the outcome of the situation. *Reflection* is essential in every learning situation. To be able to learn from experiences, individuals must reflect on their performance, and this may influence individuals' performance in following situations. The outcome of the learning process may be categorized as *change*, *confirmation* and/ or *comprehension*. The reflection process may cause changes in structures, behaviors, cognitions and practices. It may also give a confirmation that existing knowledge and practices are satisfactory, and/ or may provide a deeper understanding of established practices, tools, behavior, and working methods.

5. Tunnel Fire Safety within the Fire and Rescue Learning System

The Norwegian Fire Academy (NFA) is subjected to the Directorate of Civil Protection (DCP), and is the national educational institution for the fire and rescue services. According to the DCP, the NFA is the main source supplying the goals, contents and methods of the education (NOU, 2012:8). The current educational model is embedded in: *The regulation concerning the organization and dimensioning of the fire and rescues services* (DCP, 2003). The NFA is therefore committed to offer education and training activities in accordance with this regulation. It is claimed through the regulation, that fire and rescue personnel must have the necessary qualifications to cope with various situations and tasks, which the society may be exposed to. Further on, it is emphasized that the municipalities must conduct risk and vulnerability analysis. The purpose is to establish necessary qualifications for the fire and rescue services, and ensure adequate capability to cope with future challenges.

As of today, the education of fire and rescue personnel takes place after the employment. The educational program consists of both practical and theoretical training in the local fire department, as well as courses comprising fire protection and rescue operations under the auspices of the NFA. Internal training takes place at the local fire department where the fire and rescue personnel is employed. The training program must ensure adequate competence to help carry out the basic fire and rescue work. It is highlighted that the training and educational programs shall strive to achieve coherence between both practical and theoretical approaches (NOU, 2012:8). Following the internal training offered by the local fire department, the fire and rescue personnel must attend a basic course. This course is the final part of the education.

5.1. The notion of competence and expected learning outcomes

According to the Norwegian Official Report for the future education of the fire and rescue personnel (NOU, 2012:8), the notion of competence is understood as an accumulation of the individual's knowledge, skills and attitudes. More specifically, competence is defined as an individual not only mastering a professional field, but also being able to apply knowledge in situations that are uncertain and unpredictable. In 2018, the NFA has revised the curricula related to the basic course for the fire and rescue personnel (NFA, 2018). Under point 2.6., *Efforts in tunnel* is introduced as a topic in the course plan with the following goal; *The learner shall know about various challenges related to incidents in tunnels* (p.14). To achieve this goal, the Norwegian authorities allocate two hours with learning activities. It is expected that the learner (p.14);

- *Shall know about dangers related to efforts in tunnel (fire, rockslide, explosion, traffic accident, construction phase, PE-foam, etc.);*
- *Shall know about available equipment and how to use it;*
- *Shall know about technical installations in the tunnels and how these work, considering ventilation, communication, water, cross-section and escape routes*.

The curricula specifies that by completion of the course, the learner shall possess basic theoretical and practical knowledge and skills related to the specific subject areas (NFA, 2018).

5.2. Training facilities

Through *The tunnel safety regulation*, the importance of training activities in tunnels between the tunnel managers and the emergency services is emphasized (MTC, 2007). The Directorate of Public Roads (DPR) is the governing authority and has the responsibility of coordinating tasks to ensure that all safety aspects of a tunnel are being maintained. The directorate is also responsible for implementing necessary measures to ensure compliance with the guidelines. It is required that tunnel managers and emergency services, in cooperation, shall regularly arrange exercises for the tunnel staff and emergency services. Full-scale exercises in conditions as realistic as possible must be held in each tunnel at least every four years and smaller exercises or simulations must be held every year. *The regulation concerning fire prevention measures and inspection* requires that all tunnels that are classified as "special fire objects" shall include training and exercise designs (DCP, 2012).

6. A Modelling Framework to Increase Competence in Tunnel Fire Safety

Inspired by systems theory we combine Sommer et al.'s (2013) learning model with the feedback control loop proposed by Leveson. The model illustrated in Figure 2 aims to illustrate the “controlled learning process” by appropriate sensors (examiners, colleague evaluations etc.), controllers (decision-makers) and actuators (implementation of concrete measures) to increase competence in tunnel fire safety amongst the involved actors within the fire and rescue system. We assume it to be employed at all hierarchical levels.

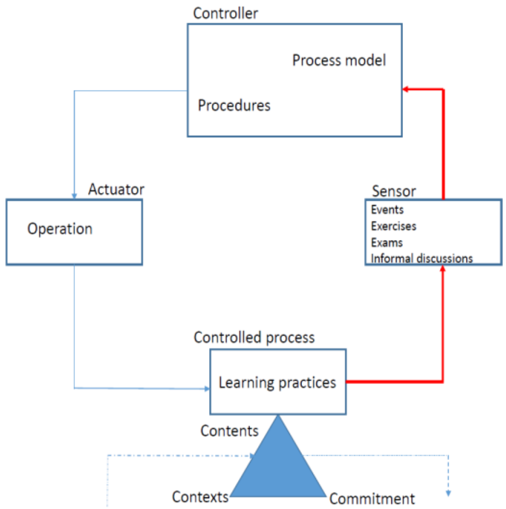

Fig. 2. Control loop to model the tunnel fire safety system adapted from Leveson (2011).

Let us illustrate the model in fig. 2 with an example. Consider a large fire department in Norwegian terms (approx. 250 000 inhabitants in its 1500 km^2 area), that has several older tunnels in its area and is in the process of obtaining several new complex tunnel structures. In this situation a new fire chief is employed, who is well acquainted with her responsibilities and the regulations for running the department. During her initial period as fire chief she experiences several major fire events in tunnels located in other areas of the country. She relates those situations to the tunnels in her area, which has also seen some minor tunnel fire events. She becomes really concerned.

Even though there are no formalized sensors yet in the system, experiences from events, risk assessments (new and existing tunnels) and informal discussions serve the purpose. The fire chief investigates the learning processes and finds practically no activity at all related to tunnel fire response. This is worrying and she alarms her owners (several municipalities) and requests risk reducing measures (actuators).

Hence, the fire chief and her staff have developed a process model to understand signals from sensors directed at the fire department’s learning processes. The control algorithm is that there is a connection between training and learning processes and the performance of the fire department in real situations. Her concerns are two ways oriented, both to protect her own employees and to serve the best rescue operations for victims (tunnel users). The situation is very complex, the fire department are on call for many single tube dual traffic tunnels, for many tunnels under construction and the fire department is involved in several complex tunnels being in their planning phase. The algorithms (procedures – models - knowledge) are associated with major uncertainties.

The choice of action (actuator) is to increase knowledge and obtain new ideas that can be adapted to the fire department’s area of tunnels. After the major fire in the St. Gotthard tunnel in 2003, Switzerland developed their center for tunnel fire rescue training. This center is approached by the fire chief to gain ideas and experiences. The fire chief also employs a dedicated person to develop courses and an educational program both for her own employees but also as a service available for other fire departments.

This example shows how the feed back control loop started and now it needs to be fueled with constraints that the fire department could be able to monitor with tools on a continuous basis. Monitoring events, exercises, exams, informal discussions and so forth is important, but what are the optimal constraints? Can it be too much focus on tunnel fires? How shall costs become balanced? Risk and safety analyses are also important tools interpreted as sensors. The management of the fire department must develop their procedures.

In order to make this system work there is a need to specify system safety constraints. This paper is an attempt to exemplify constraints directed at the learning process model in fig. 1 and also described in fig. 2. We have highlighted the intelligence part in red, because it is the part of the process that needs development at this stage. The purpose with the feedback loop is to indicate the extent to which tunnel fire safety knowledge and competence is being developed, and whether the personnel is prepared to cope with relevant tunnel fires or not.

Scenarios should be developed from risk analyses, but they are rarely seen for the purpose of learning. The environment where learning is taking place must be experienced as representing challenges that the personnel is expected to encounter in real situations. Social climate, relationships, trust and openness within the individuals must also be considered when assembling the participating group.

Our experiences, accumulated from the fire and rescue department and governing documents, have revealed that although various training and learning activities are conducted, the tunnel fire safety learning system lacks supervisory tools to monitor and give adequate feedback on the efficacy of the existing learning practices. We refer to both within the fire department, and upwards within the system's hierarchical levels. Based on this, we may assume that the decision makers possess inconsistent information concerning the actual level of competence.

7. Hazards and Safety Constraints

Although no lives have been lost in the major tunnel fires in Norway, several investigation reports have directed harsh criticism towards the safety management of the Norwegian tunnels and the emergency services' capability to deal with such incidents (AIBN, 2013; 2015/02; 2016/03; 2016/05; OAG, 2016). It has been pointed out that insufficient knowledge and competence amongst fire and rescue personnel in tunnel fire safety may lead to limitations of fire and rescue operations in the event of fire or incidents in tunnels. Despite those publications, the political authorities have not taken any steps to further facilitate the development of competence. As of today, it appears that the safety management structure of the fire and rescue learning system is flawed due to an inadequate design of control actions and lack of measures that may help mitigate the risk connected to insufficient competence in tunnel fire safety.

Below, we have identified a set of hazards related to the learning process depicted in figures 1 and 2. These hazards violates the process model of learning and will compromise competence levels in the fire and rescue services once occurred. Associated to those hazards we have developed safety constraints. Our goal is that the safety constraints can provoke discussions about vital factors for tunnel fire safety learning. A safety constraint expressing performance of learning must be designed to facilitate observation and evaluation of parts of the learning process.

Hazard 1: Inadequate design goals and expected outcomes of the tunnel fire safety learning process.

Constraints:

- Goals of the learning program must be consistent over different organisational levels for the personnel involved in tunnel fire safety work.
- Expected outcomes must comply with the goals in all learning activities planned for the fire and rescue services.

Hazard 2: Insufficient contents of fire safety phenomena and associated responses in the tunnel fire safety learning process.

Constraints:

- Ensure balance between fire dynamics, smoke exposure and the impact of safety measures for different personnel groups.
- The tunnel fire safety learning must ensure balance between flexible and standardized responses.

Hazard 3: The context of the tunnel fire safety learning process does not reflect real challenges.

Constraints:

- Ensure balance between physical and mental requirements that the personnel may encounter in a real situation.
- Ensure realistic training arenas.

Hazard 4: The tunnel fire safety learning process underestimates commitment features.

Constraints:

- Lecturers and trainers must possess necessary professional knowledge and skills, as well as pedagogical capabilities.
- The learning processes must engage personnel – motivation factor.

Hazard 5: Decision-making and responses shown in learning processes lack important factors.

Constraints:

- Develop the personnel’s ability to perform mental simulations of various scenarios.
- The training must develop the personnel’s ability to use and allocate available resources.

Hazard 6: The arenas for and expressions of reflective learning practice are worrying.

Constraints:

- Uncertainties of contents, contexts and commitments of the learning program and training activities must be discussed in groups focusing on the individuals’, team’s and service’s tasks and responsibilities.
- Cooperation between individuals, groups and teams must be part of practical reflections upon the tunnel fire safety learning program.

Hazard 7: Learners and the fire department do not show changes in their competencies.

Constraints:

- The learning program must provide changes of the participants' problem solving abilities as well as skills.
- Changes in the participants' response actions should be visible to external reviewers.

Hazard 8: Learners and the fire department do not challenge current practices.

- Current practices in tunnel fire safety work at various levels should be exposed to self-evaluation amongst practitioners.
- Cooperation and team work in the tunnel fire safety work should be scrutinized and confirmed during the learning process.

Hazard 9: There are no sign of deeper comprehension of tunnel fire safety issues.

- The learning process should achieve comprehension amongst individuals related to variations in human behavior in crisis situations.
- The learning process should achieve comprehension amongst individuals related to humans' responses to toxins from various smoke compositions.

8. Concluding remarks

This paper encompasses a recommended framework for assessing the performance of tunnel fire safety and rescue learning processes. We recognize the difficulties to monitor and control learning processes, but that does not inhibit working with the tasks. It is necessary to improve the situation, at least in Norway. Currently it is the owners of the fire departments, the municipalities, that hold the responsibilities to ensure sufficient training, but it is the tunnel owners that shall address the needs and contents. The situation is unclear and it seems that since no major fire accident has occurred investing in rather expensive training facilities is delayed. Furthermore, there are no critical voices challenging the performance of the learning processes established.

Monitoring learning processes aimed at improving fire safety and rescue in tunnels is a challenge in itself. Current tools, such as exercises, risk assessments, fire investigations, and simulations are inaccurate and unclear. We need a debate on how to set this up.

We claim that so far, no agencies have been able to establish recognized safety constraints that enables the fire and rescue services to establish necessary competence and define their own competence level. Our recommendation in this article is a first step, but the safety constraints are generalized because they are designed to be relevant for all personnel in the system hierarchy. These constraints need to be further developed by the various fire and rescue services responsible for tunnel fire safety. Enforcing constraints into the learning processes may provide valuable information to the decision-makers. Yet, this requires that the organizations systematically monitor the efficacy of the established constraints. Currently, very few is discussing performance measure able to describe the "goodness" of learning.

In this context, it is significant to emphasize that controlling learning processes represents a challenging task. Considering the fact that the fire and rescue personnel learns a great deal mostly in informal learning situations (Sommer et al., 2011), this makes the process of learning even more challenging to control, and thus require additional research related to the monitoring mechanisms.

Experiences from observational data have shown that the fire and rescue services have a high degree of freedom to implement learning and training activities regarding tunnel fire safety. It can therefore be assumed that organizations may have a varying subjective interpretation of the important aspects constituting essential knowledge and competence. We have in previous works recommended learning agents in emergency services (Njå & Svela, 2018), and we still think that this is an interesting possibility.

9. References

Accident Investigation Board Norway (AIBN) (2013). Report on fire in a heavy goods vehicle in the Oslofjord tunnel on the RV 23 road on 23 June 2011. Report road 2013/05. Lillestrøm, Norway. (In Norwegian).

Accident Investigation Board Norway (AIBN) (2015). Report on fire in a heavy goods vehicle in the Gudvanga tunnel on the E 16 Road in Aurland on 5 August 2013. Report road 2015/ 02. Lillestrøm, Norway.

Accident Investigation Board Norway (AIBN) (2016). Report on coach fire in the Gudvanga tunnel on the E 16 Road in Aurland on 11 August 2015. Report road 2016/03. Lillestrøm, Norway.

Accident Investigation Board Norway (AIBN) (2016). Report on fire in a tank trailer in the Skatestraum tunnel in Sogn og Fjordane on 15 July 2015. Report Road 2016/ 05. Lillestrøm, Norway.

Accident Investigation Board Norway (AIBN) (2018). Report on fire in heavy goods vehicle in the Oslofjord tunnel on the RV 23 road on 5 May 2017. Report Road 2018/04. Lillestrøm, Norway. (In Norwegian).

Bjelland, H. and Aven, T. (2013). Treatment of uncertainty in risk assessments in the Rogfast road tunnel project. *Safety Science*, Vol. 55, pp. 34-44.

Braut, G.S. and Njå, O. (2013). Components of a tool to address learning from accident investigation. *International Journal of Disaster Risk Reduction*, Vol. 6, pp. 40-49.

Directorate of Civil Protection (DCP) (2003). Guidance to regulation concerning the organization and dimensioning of the fire and rescue services. Capella Media, Tønsberg. (In Norwegian).

Directorate of Civil Protection (DCP) (2012): Guidance to regulation regarding fire prevention measures and inspection. (In Norwegian).

EU (2004). Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on Minimum Safety Requirements for Tunnels in the Trans-European Road Network. Brussels.

Gherardi, S., Nicolini, D. and Odella, F. (1998). Toward a Social Understanding of How People Learn in Organizations: The Notion of Situated Curriculum. *Management Learning*, Vol. 29 (3), pp. 273-297.

Hergenhahn, B.R. and Olson, M.H. (2001). *An Introduction to theories of learning*. Sixth Edition. Prentice-Hall, Inc. New Jersey.

Illeris, K. (2007). *How We Learn: Learning and non-Learning in School and Beyond*. Routledge, London.

Illeris, K. (2011*). The Fundamentals of Workplace Learning*. *Understanding How People Learn in Working Life*. Routledge. London and New York.

Kazaras, K. and Kirytopoulos, K. (2014). Challenges for current quantitative risk assessment (QRA) models to describe explicitly the road tunnel safety level. *Journal of Risk Research*, Vol. 17, No. 8, pp. 953-968.

Kolb, D.A. (1984). *Experiential learning: experience as the source of learning and development*. Englewood Cliffs, NJ: Prentice Hall.

Lave, J. and Wenger, E. (1991). *Situated learning. Legitimate peripheral participation*. University Press, Cambridge.

Leveson, G.N. (2011). *Engineering a safer world. Systems thinking applied to safety*. The MIT Press. Cambridge, Massachusetts.

Ministry of Transport and Communications (MTC) (2007). Tunnel safety regulation. (In Norwegian). Retrieved: *https://lovdata.no/dokument/SF/forskrift/2007-05-15-517*

Njå, O., Vastveit, K.R., Abrahamsen, E.B. and Eriksson, K. (2013). Evaluation of the risk assessments in the Norwegian Public Roads Administration. Report. Decision support and learning tool. IRIS-2013/043.

Njå, O., Solberg, Ø. and Braut, G. S. (2017). Uncertainty - its ontological status and relation to safety. In G. Motet, C. Bieder, & E. Marsden (Eds.), *The illusion of risk control. What would it take to live with uncertainty*. (In print - Network on Safety 2013): Springer.

Njå. O. and Svela, M. (2018). A review of the competencies in tunnel fire response seen from the first responders' perspective. *Fire Safety Journal,* Vol. 97, pp. 137-145.

Norwegian Fire Academy (NFA) (2018). Course Plan, Basic Course for the Fire Fighter 2018. (In Norwegian).

Nævestad, T.O. and Meyer, S. (2012). Vehicles fires in Norwegian road tunnels 2008-2011. Report 1205/2012. (In Norwegian).

Nævestad, T.O., Ranestad, K., Elvebakk, B. and Meyer, S. (2016). Vehicles fires in Norwegian road tunnels 2008-2015. Report 1542/2016. (In Norwegian).

Office of the Auditor General of Norway (OAG) (2016). The Office of the Auditor General's investigation of the governments work on strengthening the safety in road tunnels. Document 3:16 (2015-2016). Bergen, Norway. (In Norwegian).

Official Norwegian Report – NOU (2012:8). New education for new challenges. A comprehensive educational model for future personnel in the fire and rescue services. (In Norwegian).

PIARC – World Road Association (2008). Risk Analysis for Road Tunnels. France.

PIARC – World Road Association (2012a). Best Practice for Road Tunnel Emergency Exercises. France.

PIARC – World Road Association (2012b). Current Practice for Risk Evaluation for Road Tunnels. France.

Rasmussen, J. (1997). Risk management in a dynamic society: a modelling problem. *Safety science*, Vol. 27, No. 2/3, pp. 183-213.

Sommer, M., Njå, O. (2011). Learning amongst fire-fighters. *Journal of Workplace Learning*, Vol. 23(7), pp. 435-455.

Sommer, M., Braut, G.S. and Njå, O. (2013). A model of learning in emergency response work. *Int. J. Emergency Management*, Vol. 9, No. 2, 2013.

Time, I. and Njå, O. (2017). Approaching tunnel safety from a system safety perspective. *Safety and reliability – Theory and Applications*. ESREL 2017.