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Shelters in single-tube road tunnels: a study of the strength of knowledge

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REPORT

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SUMMARY

This study investigates shelters as a risk reducing measure for road-users enforced to self-rescue in existing single-tube road tunnels, in which smoke engulfment is a plausible emergency scenario. Once people are engulfed in smoke the uncertainties regarding toxicity and immediate danger is imminent, and there must be solutions available for the road-users within a short time span. One such solution is shelters. To avoid any value-laden terminology we have established the acronym SWETO, which stands for *Shelter Without* an exit leading to *Escape* routes *To* the *Open*. The term is stating that the rooms are connected to the outside only through the tunnel space. The Norwegian Public Roads Administration (NPRA) needs to scrutinize the possibilities to integrate SWETOs in tunnels, because the current conditions of the evacuation systems are critical.

There are no absolute requirements for emergency exits in existing road tunnels. The regulations address traffic volume as an important indicator of tunnel classification and the need of emergency exits. Previous events show that serious accidents can occur in tunnels where the traffic volume is low. The self-rescue strategy in a specific tunnel is ultimately to be based on a risk analysis and associated choice of dimensioning scenarios for the evacuation system. Integrating emergency exits in existing Norwegian road tunnels' evacuation systems is a major task in terms of costs and constructability. SWETOs are an alternative that accommodate these issues, but road owners are currently prohibited from establishing SWETOs in tunnels covered by the Directive 2004/54/EC. However, despite the current tunnel safety regulations, the NPRA takes a clear stand to incorporate SWETOs as part of the evacuation system in some single-tube, bi-directional road tunnels. The hypothesis is that shelters, given appropriate design and management, can provide a positive contribution to safety. A general prohibition, as in the EU-directive, is not reasonable. The assumption that safe shelters are merely a design issue and a sociotechnical challenge to ensure intended performance needs to be discussed.

The NPRA has initiated two pilot studies in addition to the already operational SWETOs in the Oslofjord tunnel, that include exceptions to the prohibition of "shelters without an exit leading to escape routes to the open". These projects are the Flekkerøy tunnel in Agder county municipality and the Frøya tunnel in Trøndelag county municipality. Agder county municipality and Trøndelag county municipality are obliged to participate in a follow-up R&D project after the tunnels have been built. Experiences from the pilot projects could influence any initiative to change the regulations on this matter.

The study reported in this document had the intention to update and supplement the basis already established by the R&D project "Safety management in road tunnels" (NPRA, 2020a) and concretizing the content of the R&D program for the pilot projects. Four research questions have been raised as important issues for justifying or rejecting SWETOs for long single tube bi-directional tunnels:

- RQ1: What characterizes the official European approach towards SWETOs in the work preceding Directive 2004/54/EC and the following implementation and supervision of the directive?
- RQ2: What do we currently know about Norwegian tunnel systems, major events, and previous and ongoing research that reflects the benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?
- RQ3: What does recent scientific studies contribute with in terms of supporting, contradicting and/or expanding our knowledge about benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?
- RQ4: To what extent does current knowledge support our understanding of benefits and challenges associated with SWETOs to improve the safety of tunnel users in single-tube road tunnels, and what are reasonable next steps to strengthen our knowledge?

While RQ1 is associated with understanding historical processes, RQ2-4 is about exploring what knowledge is needed to assess whether SWETOs are an appropriate safety measure in the Norwegian context or not, and subsequently what is the strength of available knowledge. The following functional requirements (FR) and connected topics were identified as a framework for collecting and analyzing the strength of knowledge:

- FR1: The tunnel and associated technical systems must be designed and constructed considering tunnel users' behavior in road tunnels in general and in accident situations specifically.
    - Driving behavior in road tunnels.
    - Human behavior in accident situations in road tunnels and situations associated with major uncertainties and stress.
- FR2: The tunnel users must be aware of and have sufficient knowledge about the safety measures in the road tunnel in case of an accident.
    - Tunnel users' general level of knowledge about tunnel safety.
    - TCC operators' ability to gain situation awareness and communicate relevant information to tunnel users.
    - Tunnel users' ability to understand and follow instructions during an evolving accident situation.
- FR3: The SWETO's construction must, over time, withstand relevant accident loads for a sufficient time to make rescue operations possible.
    - Relevant accident loads now and in the future?
    - Fire resistance of individual construction elements and combined systems' effect, e.g., fixed firefighting systems' cooling effect on wall elements.
    - Fire and rescue services' knowledge and capacity to combat relevant accident loads in road tunnels, and their ability to adjust response tactics to an emerging situation.
    - Operation, maintenance, and degradation of safety measures in road tunnels.

To investigate the status of knowledge, we initiated seven research activities (RA). RA1 was a study of public documents and literature associated with the development and implementation of Directive 2004/54/EC and RA2 included discussions with professionals involved with the same process. RA3 included the involvement of experts through a - workshop. RA4 was the development and presentation of a paper at the *International Symposium on Tunnel Safety and Security* 2023 in Stavanger. The conference normally attracts more than 200 delegates and was seen as a possible arena to present the Norwegian opinions on modern SWETOs and exploring the international response. RA5 was a study of recently published (limited to 2015-2023) literature in scientific peer-reviewed journals on the issues FR1 – FR3. RA6 was a system theoretic process analysis (STPA) of SWETOs in single-tube road tunnels, which served as a foundation for identifying functional requirements and safety constraints to SWETOs. RA7 was an analysis of available knowledge associated with FR1 – FR3 organized as a discussion.

Key findings

Our conclusion is that SWETOs, as a concept, is a relevant measure to solve a real and precarious challenge with a lack of self-rescue options in many existing Norwegian single-tube road tunnels. Available knowledge supports a stepwise establishment of SWETOs in selected high-risk road tunnels. The stepwise establishment should ensure learning from project to project. Learning must be safeguarded throughout the tunnel safety system and the value chain for SWETOs, so that functional requirements, technical solutions, operation and maintenance, and road user-oriented measures are challenged and developed in line with the experience gained from ongoing projects. We conclude that there are technologies and methods available to develop safe solutions that include the SWETO concept, but we are currently unable to define general minimum requirements for acceptably safe solutions in the relevant tunnel contexts.

Our analysis of current knowledge led to the identification of three major topics, in which we need to strengthen our knowledge and/or practices: 1) our understanding of the background for prohibiting SWETOs and opinions about future policies, 2) safety management of Norwegian road tunnels, and 3) design variables and engineering processes. The three major topics are illustrated in Figure 1. Also illustrated are the knowledge-generating activities, which includes R&D activities associated with the implementation of SWETOs in the Flekkerøy and Frøya tunnels. We have added the Oslofjord tunnel, as it represents a valuable data source of the operation and maintenance of SWETOs in the Norwegian road tunnel context. The pilot projects represent one out of many tools for knowledge generation.

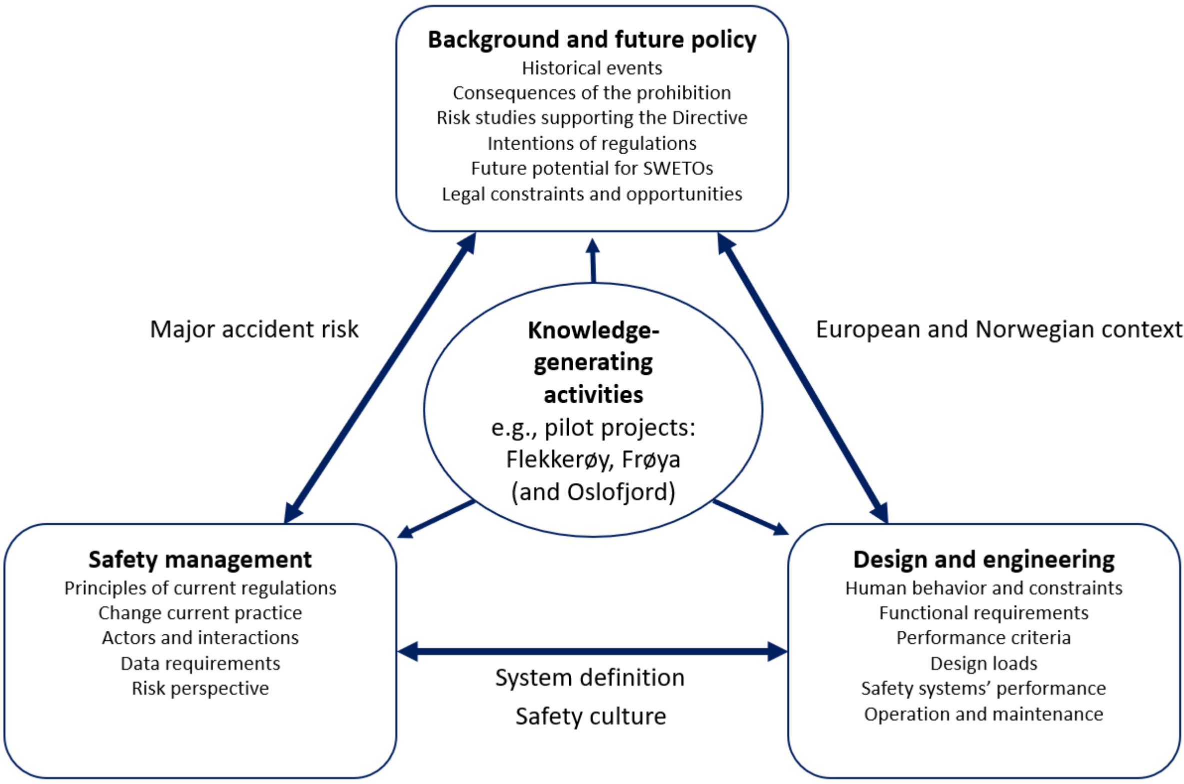

Figure 1. The structure of major topics to improve strength of knowledge to develop trustworthy evacuation concepts that includes SWETOs.

Major topic 1: Background and future policy

The study points to the Mont Blanc tunnel fire in 1999 as essential for the decision to prohibit SWETOs in road tunnels. In the years following the accident, there did not seem to be dissenting voices to the decision, which might explain why we cannot find any argumentation or considerations of risk to support the decision. However, we have identified several activities intended to reduce uncertainty about our understanding of historical events and processes, which include, e.g., a thorough investigation of available information about the Mont Blanc fire, documentation from the processes leading to Directive 2004/54/EC and interviews with key personnel from the Norwegian and European road tunnel safety community. To understand the potential for SWETOs as an element in national and/or international self-rescue strategies, we suggest a study to identify candidate road tunnels and a stakeholder analysis to explore major barriers against SWETOs in relevant tunnels.

Major topic 2: Safety management of Norwegian road tunnels

Systems thinking and active safety management is a prerequisite for adequate safety for tunnel users in road tunnels in general, and especially where SWETOs are implemented. Fundamentally, it presumes that safety is a continuous control problem where control is undertaken by the actors within the system, based on real-time information about the system's performance. Although the principles are implied by the regulations, the principles are not reflected trough the current road tunnel engineering and operational practices. A transition towards more systems thinking and active safety management on a national level is a major task, which involves changes in regulations and safety management practice. Nevertheless, to succeed with the pilot projects, we believe that it is essential to develop the concepts on these principles. This is essentially about maintaining control, and includes identifying the important actors (e.g., TCC-operators, general road users, professional drivers, first responders, etc.) and other elements (e.g., detection, positioning, communication, smoke management, etc.) of the system, who are jointly responsible for controlling safety in normal operation and self-rescue situations. The actors' and elements' connections, expectations, capabilities, and formal responsibilities need to be addressed. Active safety management prerequisite appropriate data and analyses for decision support, which are possible to develop in the context of the pilot projects.

Major topic 3: Design variables and engineering processes

The design variables and engineering processes need to reflect the fundamental principles associated with safety management (major topic 2) and the background for introducing these principles (major topic 1). The essential outcome of a safety design process, according to these principles, is a safety control plan that enable the enforcement of the system's safety constraints based on the knowledge of ongoing processes. Identifying appropriate safety constraints is a matter of analyzing the specific tunnel system, in which the pilot projects represent relevant cases. The control plan is essential to manage safety in the specific tunnels, but also to generate knowledge relevant to other tunnels and any initiative to change regulations. Several issues are identified, which need to be addressed in developing the safety control plan, for instance, functional requirements, sub-systems' performance criteria, design loads, capabilities of technical safety systems and dependency between sub-systems. More specifically, we have also highlighted the role of smoke management in relation to SWETOs, the role of distance to reduce fire exposure but also increase walking distance, uncertainty associated with human behavior in crisis situations, and issues related to operation and maintenance of SWETOs in a tunnel's lifetime perspective.

The pilot projects as a knowledge-generation tool

The pilot projects represent "living labs", where we can focus on single cases but also comparative cases. The projects represent an opportunity to approach specific actors important in the tunnel safety management, raise the actors' awareness, and study interactions between technology, actors, and safety performances. Three activities are highlighted. First, a safety study could include several elements which are highlighted under the major topics, e.g., developing functional requirements, specifying performance requirements and capabilities of involved actors, specifying dimensioning scenarios, analyzing alternative emergency response tactics, assess the interactions in cooperative emergency response situations and define requirements to the socio-technical design. The study would be basis for a project-specific control plan where the available pilot projects serve as case-studies to illustrate real challenges, scenarios, and emergency response capacities. Additionally, the study should be designed to generate transferrable knowledge to future projects and any initiative to change regulations. Second, the pilot projects should develop information and education programs targeting the actors involved in the tunnel system. Third, longitudinal research studies should be initiated to investigate the effects of implemented measures and to gather data.

Reader instructions

The report is organized with 10 sections. Section 1 introduces the study and section 2 describes methodology and study approach. Section 3 – 7 is fundamentally a background section leading to our search for updated knowledge in section 8, and our analysis and recommendations in sections 9 and 10. Readers who are primarily interested in our evaluation of available knowledge and recommendations for further research and development activities are encouraged to read section 1, 9 and 10.

Content

1 Introduction

This report investigates shelters or SWETOs, which stands for *Shelter Without* an exit leading to *Escape* routes *To* the *Open* as a risk reducing measure for road-users enforced to self-rescue, in which smoke engulfment is a plausible emergency scenario. Once people are engulfed in smoke the uncertainties regarding toxicity and immediate danger is imminent, and there must be solutions available for the road-users within a short time span. The Norwegian Public Roads Administration (NPRA) needs to scrutinize the possibilities to integrate SWETOs in tunnels, because the current conditions of the evacuation systems are critical.

1.1 Evacuation from major tunnel fires

The fundamental principle for occupant safety in case of fire in the built environment, road tunnels included, is the self-rescue principle. When an emergency occurs, drivers and passengers cannot rely on assistance, but must evacuate themselves, by vehicle or on foot (NPRA, 2022). This underlying principle will not be disputed in this report.

Road tunnels are distributed all over Norway, many of them in rural areas, far from city centers and villages where the municipal FRS' are located. Municipal FRS' are traditionally dimensioned based on the number of inhabitants, which determine both location of fire stations and organization (The Fire and Rescue Service Regulations, 2022, MJPS, 2002). The geographical location of a road tunnel is therefore important in terms of the availability and quality of the external emergency response services. Nevertheless, a fire or another emergency event may develop very quickly in a road tunnel, which means that lifesaving activities need to take place the first minutes after the event has occurred. Consequently, and unless the fire and rescue station is in the immediate vicinity of the tunnel, there is practically no alternative to adopting a self-rescue principle.

The fires in the Oslofjord (March 2011 and June 2011), Gudvanga (August 2013 and August 2015) and Skatestraum (July 2015) tunnels are characterized as "the five major Norwegian road tunnel fires" (Amundsen, 2017). Even if there were no fatalities, the fires are a reminder of the major consequence potential in tunnel fires. The events revealed challenges associated with evacuation from single-tube road tunnels in major fires. After the "major five" and other serious fire events since 2011, the Norwegian Safety Investigation Authority (NSIA) raised harsh critiques towards the NPRA, claiming that the premises for successful self-rescue is generally not in place for long single-tube tunnels without emergency exits. The critiques point to the fact that facilitation of self-rescue is a shared responsibility, in which the tunnel system needs adaption to the users' prerequisites and limitations. The testimonies from the tunnel users involved in the Oslofjord tunnel fire in 2011 (NSIA, 2013, Njå and Kuran, 2014) and in the Gudvanga tunnel fires in 2013 and 2015 (NSIA, 2015, NSIA, 2016b), illustrate that evacuation from a road tunnel can be a very difficult and represent traumatic experiences. The main problems for tunnel users were caused by movement in dense smoke, which is partially explained by the relatively late initiated evacuation. The "communication" between the tunnel infrastructure and the road users in case of emerging fire situations must be improved.

1.2 Can SWETOs improve the evacuation system?

Safe SWETOs were proposed as feasible solutions for tunnels in the period where the Norwegian infrastructure as well as international road infrastructure became significantly developed (1950s to 1970s). Frøholm's triology (Frøholm, 1970, Frøholm, 1971, Frøholm, 1972) introduces the period's state of the art in tunneling and major concerns related to risks. Fires in heavy goods vehicles were rarely experienced. Safe SWETOs with fresh air were proposed for people being trapped in tunnels exposed to a polluted atmosphere from exhaust substances. Sufficient ventilation was a major concern at that time. This legacy has influenced the subsequent development of safety measures in tunnels.

There are no absolute requirements for emergency exits in existing road tunnels. For new tunnels, the EU directive states that emergency exits shall be provided where the annual average daily traffic (AADT) exceeds 2 000 vehicles per lane. Norway has been granted the possibility of approving exceptions for tunnels shorter than 10 km and with an AADT of less than 4 000 vehicles per lane, given that a risk analysis can demonstrate an equivalent or higher level of safety.

Despite the current tunnel safety regulations, the NPRA takes a clear stand to integrate SWETOs as part of the evacuation system in single-tube, bi-directional road tunnels. In 2015, NPRA (Søvik and Henning, 2015) proposed measures to improve fire safety in risk prone[1] road tunnels as a response to the fires in Oslofjord, Gudvanga and Skatestraum tunnels. The report lists a set of measures to improve fire safety. SWETOs are considered as a relevant safety measure in some of the risk prone tunnels, i.e., "longer single-tube road tunnels with special characteristics". Amundsen, a prominent employee with respect to tunnel safety in the NPRA stated that SWETOs were recommended, but he raised concerns about the practical use of SWETOs in emergencies, how the shelters should be designed and equipped and what types of fires should represent the design load (Amundsen, 2017).

The NPRA initiated the research project *Safety management in road tunnels 2017-2019* (NPRA, 2020a). The project sought to address questions from previous reports and included several studies in cooperation with SINTEF and Lund University: a literature study about evacuation from road tunnels (Jenssen et al., 2017), a VR-study simulating evacuation in a road tunnel (Jenssen et al., 2018) and a VR-study on the human experiences of different shelter designs and equipment (Jenssen et al., 2020). The results of the investigation were positive towards integrating SWETOs in the evacuation systems, which led to the following recommendation:

> *"An application is sent to the Ministry of Transport/EU (ESA) in order to approve the use of evacuation rooms without exit to the outdoors in long single-tube road tunnels in Norway for temporary stay as part of assisted rescue" (NPRA, 2020a)*.

In a letter to the Ministry of Transport (NPRA, 2020b), the Norwegian public roads directorate (NPRD) applied for an exemption from the Norwegian Tunnel Regulation (FOR-2007-05-15-517) to obtain approval to be able to use SWETOs without access to the outdoors in long single-tube road tunnels for temporary accommodation as part of assisted rescue. The application concerned the TEN-T road network in Norway but would also apply for other national roads and county roads in Norway if the exception would become granted.

1.3 Research questions investigated in the study work

The NPRD assesses whether the use of SWETOs can provide an efficient and cost-effective measure to improve self-rescue in long single-tube tunnels. The self-regulation principle, the cooperation principle, and the principle of universal design, all point to the need for developing a proper system for self-rescue. The hypothesis is that SWETOs, given appropriate design and

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[1] Single-tube road tunnels with over 12 000 vehicle kilometers/day and longer than 3 kilometers and/or one-lane road tunnels over 1 km with a gradient of more than 5 % and/or one-lane road tunnels over 5 km.

management, can provide a positive contribution to safety, and that a general prohibition, as in the EU-directive, is not reasonable. The assumption that safe SWETOs are merely a design issue and a sociotechnical challenge to ensure intended performance needs to be discussed.

We approach the research study in two steps where this study is a preliminary **first step.** The project is carried out as a collaborative project under the Capacity Boost Tunnel Safety (KATS) program, in which the Norwegian Public Roads Administration (NPRA) is a partner. The aim of the preliminary project is to update and supplement the basis already established by the R&D project "Safety management in road tunnels" and concretize the content of the R&D program for the pilot projects. A prerequisite is that the overall goals with the pilot projects are defined and agreed upon.

The following research questions have been raised as important issues for justifying or rejecting SWETOs for long single tube bi-directional tunnels. The first research question is concerned with our collective understanding of why SWETOs are prohibited:

- **RQ1:** What characterizes the official European approach towards SWETOs in the work preceding Directive 2004/54/EC and the following implementation and supervision of the directive?

Second, this study builds on the assumption that the Norwegian Ministry of Transportation considers that existing knowledge and experience is deficient to initiate a process with the EU with the aim of revising the Directive 2004/54/EC to accept SWETOs. Considering that there could be several justifications for improving tunnel safety in a country such as Norway, it is considered necessary to establish an understanding about existing knowledge and experience:

- **RQ2:** What do we currently know about Norwegian tunnel systems, major events, and previous and ongoing research that reflects the benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?

Third, this study is also aiming to include recent and relevant scientific knowledge to supplement the literature study (Jenssen et al., 2017) conducted as part of NPRA’s R&D project "Safety management in road tunnels" (NPRA, 2020a):

- **RQ3:** What does recent scientific studies contribute with in terms of supporting, contradicting and/or expanding our knowledge about benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?

While research questions 1-3 have a descriptive nature, the study aims to provide recommendations for further actions to strengthen our knowledge about the benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels. Consequently, we introduce a final research question to support normative recommendations:

- **RQ4:** To what extent does current knowledge support our understanding of benefits and challenges associated with SWETOs to improve the safety of tunnel users in single-tube road tunnels, and what are reasonable next steps to strengthen our knowledge?

The NPRA have initiated two pilot studies in addition to the already operational SWETOs in the Oslofjord tunnel, that include exceptions to the prohibition on "shelters without an exit leading to escape routes to the open". These projects are the Flekkerøy tunnel in Agder county municipality and the Frøya tunnel in Trøndelag county municipality. Agder county municipality and Trøndelag county municipality are obliged to participate in a follow-up R&D project after the tunnels have been built. Experiences from the pilot projects should strengthen any initiative to change the regulations on this matter. Until such experiences are gathered, the NPRD will not grant exceptions related to SWETOs in other tunnels. Under RQ4 we will investigate how the two pilot projects serve as knowledge generating evidence on the performance of safe SWETOs.

1.4 Terminology

The key issue in this report is what the Directive 2004/54/EC specifies as "shelters without an exit leading to escape routes to the open". In the Norwegian tunnel safety regulation, they are referred to as "tilfluktsrom". In discussions amongst professionals and in the literature, we find that the rooms are referred by different terms. Some examples are:

- Emergency shelters
- Evacuation shelters or evacuation rooms
- Rescue shelters or rescue rooms
- Waiting room for assisted evacuation
- Safe havens or safe areas

It is of great interest what these rooms are called, as there seem to be a strong connotation to the room's purpose or function. This is further discussed in section 9.3.5, but to avoid any value-laden terminology we establish the acronym SWETO, which simply stands for *Shelter Without* an exit leading to *Escape* routes *To* the *Open*. The term is stating that the rooms are connected to the outside only through the tunnel space. We will also use the term "shelters" in the text with the same meaning, as it is more intuitively understandable. If we discuss shelters *with* an exit leading to escape routes to the open, this will be explicitly mentioned.

Table 1 depicts the meaning of acronyms that we regularly use in the report.

Table 1. Acronyms and abbreviations

Acronym	Description
AADT	Average Annual Daily Traffic
AID	Automatic Incident Detection system
ATMB	Autoroute et Tunnel du Mont Blanc. Tunnel operator in the French side of the Mont Blanc tunnel in 1999.
CETU	Centre d'Études des Tunnels, France.
CFD	Computational Fluid Dynamics
Directive 2004/54/EC	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
FEMA	United States' Federal Emergency Management Agency.
FRS	Fire and rescue service
HGV	Heavy Goods Vehicle
IFA	International Fire Academy, located in Balsthal, Switzerland.
KATS	Capacity boost tunnel safety. Research and innovation project led by the University of Stavanger.
LED	Light Emitting Diode
MDC	Medical dispatch center, i.e. the "113 central".
NPRA	Norwegian Public Roads Administration
NPRD	Norwegian Public Roads Directorate

Acronym	**Description**
NSIA	Norwegian Safety Investigation Authority
SCADA	Supervisory control and data acquisition system
SWETO	*Shelter Without* an exit leading to *Escape* routes *To* the *Open*
TCC	Traffic control center (Vegtrafikksentralen)
TEN-T	Trans-European Transport Network
FFFS	Fixed Firefighting Systems
TSR	The Norwegian tunnel safety regulation, FOR-2007-05-15-517
TSRR	The Norwegian tunnel safety regulation for regional roads, FOR-2014-12-10-1566
VMS	Variable message sign
VR	Virtual reality

2 Methodology and study approach

In this study we reinvestigate SWETOs as a safety measure to improve the safety of users of single-tube road tunnels in critical events. The research questions we answer in this report is:

- **RQ1:** What characterizes the official European approach to SWETOs in the work preceding Directive 2004/54/EC and the following implementation and supervision of the directive?
- **RQ2:** What do we currently know about Norwegian tunnel systems, major events, and previous and ongoing research that reflects the benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?
- **RQ3:** What does recent scientific studies contribute with in terms of supporting, contradicting and/or expanding our knowledge about benefits and challenges of SWETOs to improve the safety of tunnel users in single-tube road tunnels?
- **RQ4:** To what extent does current knowledge support our understanding of benefits and challenges associated with SWETOs to improve the safety of tunnel users in single-tube road tunnels, and what are reasonable next steps to strengthen our knowledge?

Answering RQ1 involves gaining an overview and understanding of the processes initiated in the vicinity of the European Parliament, and connected documentation, from the late 1990s to the development and implementation of Directive 2004/54/EC. While RQ1 is associated with understanding *historical processes*, RQ2-4 is about exploring *what knowledge is needed* to assess whether SWETOs are an appropriate safety measure in the Norwegian context or not, and what is the *strength of available knowledge*.

2.1 The need for intermediate variables to study

Until SWETOs was prohibited following Directive 2004/54/EC, shelters in different formats have been a part of European road tunnel designs. For instance, Frøholm (1970) describes the plans for the new St Gotthard tunnel from 1969, where it was decided to implement evacuation shelters, connected to a fresh air canal, every 250 meters. The author suggests that such solutions should be considered for Norwegian tunnels as well. However, SWETOs did not become a natural part of the Norwegian tunnel construction tradition. What we have, is a great number of single-tube road tunnels with bi-directional traffic. There are no evacuation possibilities besides the tunnel's two portals. From a methodological point of view, this means that we have a very limited sample of SWETOs to study in Norway. In fact, the Oslofjord tunnel is the only road tunnel where SWETOs have been operational since the tunnel was upgraded with such rooms after a major fire in 2011, which was by incident discovered in the investigation of the fire. It also means that the sample of European road tunnels, that included SWETOs as part of the evacuation strategy, is aging. Since the early 2000s, there have been major developments in wayfinding systems and communication technologies, which presumably affect the efficiency of SWETOs. This means that we need to critically review the experiences from old fire events and what it says about modern tunnel systems and SWETOs.

SWETOs are measures that are intended to operate in critical situations. Such rare situations will comprise immediate danger of tunnel-users meaning they might be engulfed in smoke. Tunnel-users need to know that the SWETOs are available and understand when it is appropriate to use the SWETOs. Generally, the sample of road tunnels including SWETOs are limited and the sample of previous events in which SWETOs were part of the evacuation concept is even more limited. This leads to the challenge associated with any novel safety measure which is intended to reduce major accident risks. It is challenging to measure its safety performance by counting the number of lives and injuries prevented. Consequently, we need to develop an alternative method to consider the quality of available knowledge to assess the safety effects of SWETOs.

2.2 Topics to consider

Our approach in this study has been to work from a set of functional requirements, which would be reasonable to enforce on a tunnel system that includes SWETOs. Based on the functional requirements, we identified a set of connected topics by which we investigate the status of knowledge. The functional requirements are derived by having a narrative of a fire scenario in mind, which could be summarized as follows:

> *Depending on the situation, the vehicles in a road tunnel might be driving with major individual distances, in groups behind slow vehicles, or in a continuous stream of different types of vehicles. On a particular day and time, something unordinary happens to one of the vehicles in the tunnel, it catches fire. The driver may not notice the fire immediately and continues driving. At some point, both the driver and other tunnel users will experience symptoms that something is out of the ordinary, and there might be a need, for many people, to adapt to a new and uncertain situation. When the traffic comes to a stop, vehicles might be piling up on either side of the vehicle on fire. Some drivers might attempt to pass the burning vehicle, others will turn around and drive out, and some will wait for further instructions. Their actions may be influenced on the example of others, previous knowledge with similar situations or guidance from the tunnel infrastructure and communication systems. Their actions might also be constrained by the tunnel geometry, lightning conditions, smoke affecting their sight, and their own psychological reaction to the uncertain situation. Traffic control operators will at some point in time become aware of the situation. The time and content of their available information are dependent on what surveillance systems are present in the tunnel and/or the information gained from tunnel users. If the tunnel is not closed for traffic automatically, traffic control operators will initiate actions to do this, and connect with external emergency responders. The operators' further actions are constrained by the available equipment in the tunnel. If tunnel users become trapped in the smoke, they might consider waiting in their vehicle for assistance or attempt to evacuate through the tunnel space. Rationally thinking tunnel users will know that the portals are safe places, but they might be unaware that there are emergency exits or SWETOs inside the tunnel tube. Awareness might be raised by following the example of others, through instructions from tunnel operators, or by guidance systems available in the tunnel. When the evacuees find an emergency exit, they might understand that this leads to a safer place than the tunnel space and attempt to enter. The door will be operational or not, depending on maintenance and exposure to heat. If the emergency exit leads to a shelter, the shelter will be occupied by others or not. The shelter might, by its initial occupants, be considered as full. Occupants in the shelter will be protected from hazardous conditions in the tunnel space, but if the accident loads from the outside becomes too large, the room might fail to protect its occupants before they are rescued by external emergency responders. The time it will take to rescue occupants, and the capacity of the emergency responders, will depend both on regional variations and the tunnel's safety systems.*

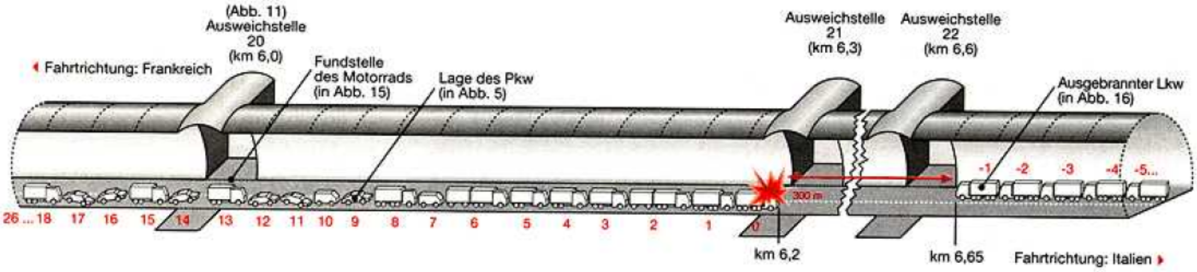

Figure 2. The Mont Blanc Tunnel, left to France, right to Italy. Copyright Brandschutz 8-99 (Landrover Club, 2002).

The selected functional requirements and connected topics are:

- *FR1: The tunnel and associated technical systems must be designed and constructed considering tunnel users' behavior in road tunnels in general and in accident situations specifically.*
    - Driving behavior in road tunnels.
    - Human behavior in accident situations in road tunnels and situations associated with major uncertainties and stress.
- *FR2: The tunnel users must be aware of and have sufficient knowledge about the safety measures in the road tunnel in case of an accident.*
    - Tunnel users' general level of knowledge about tunnel safety.
    - TCC operators' ability to gain situation awareness and communicate relevant information to tunnel users.
    - Tunnel users' ability to understand and follow instructions during an evolving accident situation.
- *FR3: The SWETO's construction must, over time, withstand relevant accident loads for a sufficient time to make rescue operations possible.*
    - Relevant accident loads now and in the future?
    - Fire resistance of individual construction elements and combined systems' effect, e.g., fixed firefighting systems' cooling effect on wall elements.
    - FRS' knowledge and capacity to tackle relevant accident loads in road tunnels, and their ability to adjust response tactics to an emerging situation.
    - Operation, maintenance, and degradation of safety measures in road tunnels.

We will discuss these issues in section 9.

2.3 Research activities (RA) and connection to research questions

The study comprised the following research activities:

RA1: Document study in the vicinity of the European Parliament in the late 1990s to the time of development and implementation of Directive 2004/54/EC. The study included a search for preparatory work for Directive 2004/54/EC in the EU database. The study also included documentation associated with professional and political processes that followed the major fires in the Mont Blanc, St. Gotthard, and Tauern tunnels in the late 1990s and early 2000s. References in the documents were actively used for snowballing to find important foundational work. We also conducted a literature search in Scopus, as well as all the historical proceedings from the *International Symposium on Tunnel Safety and Security* (ISTSS), targeting articles that dealt with the background, development, and implementation of Directive 2004/54/EC.

RA2: Interviews and informal discussions with professional time witnesses. As part of the study, we reached out to our national and international network to discuss the background and justification for implementing a prohibition of SWETOs in Directive 2004/54/EC. We were specifically interested in the opinions of those closely involved with the post-fire investigations of Mont Blanc (1999) and the development of Directive 2004/54/EC. Findings from RA1 show that France and representatives from CETU were central in this work and were prioritized in this pre-study. Through a partner in KATS, we established an email correspondence with a prominent actor within European tunnel safety. They both provided us with information about the processes of the time. We also initiated informal discussions with previous employees of the NRPA, who were intimate with the European discussions and the Norwegian implementation of Directive 2004/54/EC.

RA3: Expert involvement through a workshop and its follow-up actions. The workshop had two purposes: 1) to present relevant knowledge associated with SWETOs as a safety measure in Norwegian single-tube road tunnels, and 2) discuss what knowledge gaps that need attention if we backcast from a future where SWETOs are part of the evacuation system in selected Norwegian road tunnels. The workshop gathered 28 participants from tunnel management, TCC, FRS, regulatory agencies, consultancies and academia in Oslo, April 12, 2023. The workshop was also extended by an input memo, authored by Multiconsult about geological concerns and constructability of SWETOs in Norwegian road tunnels. To supplement the workshop further, we invited Dr. Gunnar D. Jenssen at SINTEF, Professor Ove Njå at the University of Stavanger and Dr. Jonatan Gehandler and Professor Haukur Ingason at RISE Fire Research, to produce notes on relevant current knowledge, seen from their respective areas of research.

RA4: Paper presented at ISTSS 2023 (Kjos et al., 2023). The ISTSS attracts tunnel safety researchers and professionals from all over the world. In 2023, the bi-annual conference was held April 26 - 28, 2023 in Stavanger, Norway. This was seen as a possible arena to present the Norwegian opinions on modern SWETOs and exploring the international response. The activity included the development, submission and presentation of a research paper and follow-up discussions during the conference. It is worth noting SWETOs were a topic of a whole session at the conference and became a topic in plenary discussions from the stage. The paper was selected for further development and potential publication in the peer-reviewed scientific journal *Fire Safety Journal*, which indicates that there is support beyond Norwegian borders to further consider SWETOs as a part of the evacuation system in selected single-tube road tunnels.

RA5: Scientific literature study. It was a predetermined goal that this pre-study work should update the literature study conducted as part of NPRA's R&D project "Safety management in road tunnels" in 2017. As mentioned above, the sample of SWETOs in road tunnels are small and the sample of events including SWETOs is even smaller. Consequently, we developed the functional requirements (FR 1-3) and associated topics, which would be investigated for scientific knowledge. The literature study was conducted using the library at the University of Stavanger and its subscription to scientific databases, focusing on literature published since the previous study in 2017. The literature study was limited to peer-reviewed articles published in Norwegian or English and within a time frame of 2015 until 1st September 2023 (when the search commenced). Where the articles referenced older research, which was important for our study, the snowball method was used.

The literature study was performed as a scoping study to find a broad perspective of peer-reviewed articles on the different topics defined by the functional requirements and understand what types of research had been published since 2015. For each functional requirement several research questions were formed, as well as search word combinations and inclusion criteria.

Topics which were excluded from this literature search were:

- Fire resistance of construction elements using common testing methods, meaning more common fire durations of several hours
- Accident loads for today's traffic, as these topics are well known after several large fires in Norway and through the contribution of RISE in section 7.4.
- FRS' knowledge and capacity; as we build on the recent study by Bjørnsen et al. (2023a).

The following databases were used:

- *Academic Search Premier*
- *Scopus*; which among others includes *Science Direct, Fire Safety Journal, Fire Technology* and *Tunneling and Underground Space Technology*
- *Web of Science*

The following search strategy was used during the literature search:

- *First screening*: Search within abstract title, abstract and keywords for words within eligibility criteria, then scan through search results in title and abstract for relevance according to inclusion & exclusion criteria.
- *Second screening*: Relevant articles found in first screening, second screening will include reading introduction, results and conclusion assessing according to inclusion & exclusion criteria.

Search results are presented in Table 2.

Table 2: Results from literature search

Search topic	**Search findings**	**First screening**	**Second screening**
Driving behavior in road tunnels	n= 323	n= 24	n= 6
Human behavior during evacuation	n= 278	n= 26	n= 16
Tunnel users' general level of knowledge about tunnel safety	n= 238	n= 8	n= 5
TCC operators' ability to gain situation awareness and communicate	n= 2.445	n= 15	n= 7
Tunnel users' ability to understand and follow instructions	n= 55	n= 11	n= 5
Relevant accident loads in the future	n= 1 503	n= 71	n= 17
Fire resistance of individual construction elements and combined systems' effect, e.g., fixed firefighting systems' cooling effect on wall elements	n= 476	n= 21	n= 12
Operation, maintenance, and degradation of safety measures in road tunnels.	n= 677	n= 9	n= 0
Research on the use or design of SWETOs	n= 3.438	n= 17	n= 0
TOTAL =	n = 9 433	n = 202	N = 68

<u>RA6: System theoretic process analysis (STPA) of SWETOs in single-tube road tunnels.</u> As part of the ongoing PhD-education of Jeroen Wiebes Kjos, a STPA-analysis was conducted to supplement this pre-study. STPA analyses builds on systems theory (Leveson, 2011) and introduces a top-down approach to study the performance of safety systems. From the analysis, we identified important functional requirements and system level hazards that need to be addressed, and ultimately prevented by enforcing safety constraints. It was not a goal in the project to identify acceptable designs or solutions, but rather to explore the variety of possible safety constraints from a broad socio-technical perspective. The work served as a foundation for identifying functional requirements and safety constraints to SWETOs, which are introduced and discussed several times in this report.

<u>RA7: Analysis of available knowledge through discussion.</u> The goal of this study is to point at reasonable next steps to improve the strength of knowledge about the challenges and benefits of SWETOs as part of the evacuation system in selected single-tube road tunnels. The recommendations should be organized either as suggested actions to implement in 1) two ongoing pilot projects that include SWETOs in existing road tunnels on county roads, or 2) general actions which would strengthen the knowledge needed to initiate a discussion with the EU about SWETOs in single-tube road tunnels. Evidence based research related to real

time performance with respect to life and injury prevention is not a feasible approach. On the contrary the focus needs to be kept on intermediate quantities that might point to the SWETO's performance in case of emergent critical events.

Table 3. Connection between research questions and research activities.

	RA1: Public literature study	RA2: Interviews and informal talks	RA3: Expert knowledge	RA4: ISTSS paper	RA5: Scientific literature study	RA6: STPA-analysis	RA7: Analytical discussion
RQ1: Directive 2004/54/EC	X	X		X	(X)		
RQ2: Current knowledge			X				
RQ3: Recent scientific advancements			(X)		X		
RQ4: Strength of knowledge and next steps?					X	X	X

2.4 Structure of the report

The report is structured in the following major sections:

- Introduction (chapter 1): Introduces the topics and the reasons for conducting this pre-study.
- Methodology and study approach (chapter 2): Introduces the research questions and describes the methods used to generate knowledge associated with the research questions.
- Results (chapter 3-8), where sections 3-7 are concerned with "current knowledge" and section 8 is the results of a literature study of recent scientific studies that supports, contradicts and/or supplement our current knowledge.
- Analytical discussion (chapter 9): Presents a discussion structured around important functional requirements that are essential to meet if SWETOs are to become an integral part of evacuation systems in Norwegian road tunnels. The aim of this section is to reflect on available knowledge and identify relevant actions to bridge knowledge gaps.
- Recommendations to future research and engineering issues: This section aims to summarize recommended actions. The suggested actions are categorized under three major topics, which we recommend that NPRA develop further. A model is developed to show the connection between the major topics, and how specific research and development activities in the two defined pilot projects (Flekkerøy and Frøya) could support knowledge-development within the major topics.

3 Background, context, and implementation of Directive 2004/54/EC

By the end of the 1990s, there were outdated operational tunnels all over Europe. The tunnels were built in accordance with specifications that no longer corresponded to safety standards, or the traffic conditions had substantially changed from the original design premises. Legal mechanisms at national level were lacking to oblige tunnel managers to improve safety once the tunnels were put in operation (Thamm, 2003). Lacroix (2008) describes a situation where tunnel safety had been an urgent matter in the European professional community for years preceding the Mont Blanc and Tauern tunnel fires in 1999. A substantial contribution was the EUREKA project EU 499 FIRETUN, initiated by STUVA[2] in Germany. In the early 1990s, nine European nations cooperated about instrumenting and conducting full-scale fire experiments in the 2300-meter Repparfjord tunnel in northern Norway. The project was based on an acknowledgement that fire risk in European tunnels was on a rising trend, for instance due to the growing density of traffic, more and longer tunnels and increase in vandalism (Grønhaug, 1990, Haack, 1998). In 1994, the results from the EUREKA project and other initiatives were presented at the International Conference on Fires in Tunnels in Borås, Sweden (SP, 1994). Despite academic and professional interest, it was not until the major accidents occurred that heads of States asked the European Commission to address the matter, and the European Union really became involved. The first initiative was to include tunnel safety as a subject in calls for research tenders (Lacroix, 2008).

Thamm (2003) points to the European Council's meeting in Laeken, December 2001, which underlined the urgency for an initiative to improve tunnel safety on the European level. The disruption of the transport system following major fires were also emphasized. Subsequently, the EU Commission decided to prepare a legislative instrument in the form of a directive, which was approved 29 April 2004. The directive should answer to the need of harmonizing safety information, communication, and equipment to increase safety for travelling Europeans. Both Lacroix (2008) and Thamm (2003) emphasize that the basis for the technical requirements included in the draft directive was the work conducted by the ad hoc working group on road tunnel safety of the Economic Commission of the United Nations (UN-ECE), and the World Road Association (PIARC) committee C3.3 Road Tunnel Operations. The expert group was chaired by Michel Egger, Deputy Director of the Swiss Federal Roads Authority (FEDRO) and co-chaired by Didier Lacroix, Research Director at Centre d'Études des Tunnels (CETU) in France. Lacroix was also central in developing PIARC recommendations, as the leader of a working group devoted to "Fire and smoke control" under PIARC's C3.3 committee, and as the chairman of a Joint OECD/PIARC Scientific Working Group on dangerous goods in road tunnels. Norway was represented in the mentioned PIARC working group and the Joint OECD/PIARC Scientific Working Group by Mr. Finn Harald Amundsen from the NPRA (PIARC, 1999, OECD/PIARC, 2001). In the early 2000s, the EU initiated several research projects on tunnel safety (FIT, UPTUN, DARTS and SafeT), in which several of the members of PIARC C3.3 participated. According to West (2004), "the contact via this committee helped to improve networking and avoid duplication of efforts. Through common members C3.3 received regular updates on the work of all of these studies"

The French regulations, which dated back to 1981, was already under revision when the Mt.

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[2] STUVA: Studiengesellschaft für unterirdische Verkehrsanlagen

Blanc fire occurred in 1999. Existing regulations only applied to new tunnels, but the Mt Blanc fire showed that it was essential to also cover existing tunnels. Immediately following the Mt Blanc fire, measures were taken in France to improve the safety of existing tunnels and tunnels under construction. An Inter-ministry Circular dated 25 August 2000 included technical instructions, design and operation rules which built on legislative work conducted before the Mt Blanc fire and included lessons learnt from the fire. According to Lacroix (2008), the Directive 2004/54/EC is heavily influenced by the French system implemented in the early 2000s. At the time, France had 30 national tunnels and three tunnels shared by neighbor countries in operation, which would fall under the scope of the directive. As a comparison it was considered that 409 Norwegian road tunnels, of which 115 on TEN-T roads, would fall under the scope of the directive (MFA, 2006).

Lacroix (2008) describes the work conducted by the Western European Road Directors (now the Conference of European Directors of Roads – CEDR) to harmonize various national initiatives. A working group comprising representatives from all Alpine countries produced recommendations that were approved by WERD / CEDR in September 2000. Lacroix (2008) highlights the work of a Swiss federal commission, which was established after the Mont Blanc fire in 1999. The commission produced recommendations related to tunnel users, operation, infrastructure, and vehicles, as important for CEDR's recommendations. The recommendations from CEDR were further revised and extended by UN ECE's multidisciplinary expert group on road tunnel safety. Their final report of recommendations for improving road tunnel safety was completed in December 2001.

3.1 Influential works leading towards the Directive

In this section we have included a chronological description of some of the influential work leading towards the Directive 2004/54/EC.

Commission of the European Communities (1997). *Promoting road safety in the EU. The programme for 1997-2001*. Brussels, April 9, 1997 (EC-COM, 1997).

The report represented the European Commission's concerns about the great number of victims and the associated high costs of traffic accidents in European countries. It emphasized the need to perceive road causalities in a system perspective, i.e. as "failures in complex systems of human decisions and actions, a variety of infrastructures and all kinds of vehicles" (p. 17). The authors claimed that there was a great potential in developing a more accident-friendly infrastructure across the member states of the European Union, in which the human factor was given due consideration. Several actions were included to improve road safety in the report's annex III. However, tunnel safety was not a topic which was addressed specifically in the suggested program.

Commission of the European Communities (2001). White paper: European transport policy for 2010: time to decide. Brussels, September 12, 2001 (EC-COM, 2001).

In the report, the European Commission stated that "safety in long tunnels is another vitally important aspect in the development of the trans-European network" (p. 57). Based on three arguments: 1) several major upcoming tunneling projects, 2) the aging of the existing tunnel population, and 3) the great variation of current national legislations for tunnel safety, the commission pointed to the need of developing common "European regulations, which could take the form of a directive on the harmonisation of minimum safety standards, so as to put in place the conditions guaranteeing a high level of safety for the users of road and rail tunnels, particularly those forming part of the trans-European transport network" (p. 58).

UN (2001). Recommendations of the group of experts on safety in road tunnels – final report. United Nations Economic and Social Council, December 10, 2001 (UNECE, 2001).
According to the report, safety in road tunnels was a concern before the fires in 1999 in the Mt. Blanc and Tauern tunnels. However, the dramatic events of 1999 "brought the risks in tunnels to the forefront and led political leaders to get involved." In parallel with national actions undertaken after the accidents, the UN established an ad-hoc expert group on tunnel safety, that was given the task of giving "recommendations for minimum requirements concerning safety in tunnels of various types and lengths". According to PIARC (2008b), these recommendations was one of the most influential inputs for developing the "Directive of the European Parliament and Council on minimum safety requirements for tunnels in the Trans-European Road Network" (PIARC, 2008b).

The UN's expert group perceived road tunnel safety as an interplay between road users, operation, infrastructure, and vehicles. This indicates a system perspective, not unlike the thoughts presented by the European Commission in 1997 (EC-COM, 1997). The human factor was greatly emphasized. Prioritization of safety measures should follow the primary objective of preventing accidents, and the secondary objective of reducing consequences of accidents. The prioritization was a consequence of the observation that time is a critical factor in road tunnel accidents: "In the event of an incident, the first ten minutes are decisive when it comes to people saving themselves and limiting damage. The prevention of critical events is therefore the number one priority, which means that the most important measures to be taken have to be of a preventive nature" (UNECE, 2001).

The expert group recommended several measures under the categories 1) road users, 2) operation, 3) infrastructure and 4) vehicles. Under category 3 and sub-category "emergency exits", the expert group stated that "shelters without an exit leading to escape routes to the open represent an unacceptable risk; this type of closed-in shelters should not be built any more" (UNECE, 2001). The report does not, however, present the reasoning behind this opinion towards SWETOs.

European Council (2001). *Presidency conclusions: European Council meeting in Laeken, 14 and 15 December 2001 (EC, 2001).*
In the Laeken declaration of December 2001, we find the following decision: "The dramatic accident in St Gotthard (24 October 2001), following on the Mont-Blanc accident, demonstrates the urgency of measures to transfer goods haulage from road to rail. The Commission will submit its framework proposal on (…) tunnel safety as soon as possible" (EC, 2001).

OECD & PIARC (2001). *Safety in tunnels. Transport of dangerous goods through road tunnels.* Organisation for Economic Co-operation and Development. Paris, France (OECD/PIARC, 2001).
The OECD was concerned about the increase of road transport, and especially heavy goods transport in existing road tunnels. In addition, the number of new tunnels was increasing. It was recognized that techniques concerning tunnel construction and safety were steadily improving, but the challenges associated with dangerous goods were not dealt with satisfactorily. Regulations in different countries specified various levels of restrictions, and it was noted that tunnel-rich countries, such as Norway and Italy, had less restrictions than countries with few tunnels. Consequently, the OECD report included a recommendation of harmonizing regulations and develop tools to assess the risk associated with dangerous goods transport in road tunnels, i.e., the Quantitative Risk Assessment Model (QRAM) and the Decision Support Model (DSM). The categories of dangerous goods classification (A-E), which

is in use in Norwegian tunnels today, was derived and presented in the report. The backdrop of the report was a recognition that a large explosion, a large toxic gas release and large fires could have major consequences and limited mitigation possibilities. Still, there was risk associated with transporting dangerous goods on alternative routes, which called for systematic risk assessments of the alternatives and implementation of other decision-relevant information.

A set of 33 fires in heavy goods vehicles from 1949 – 1999 was studied by OECD. Data from 22 of the fires are reported in a Table 4, which is reproduced as Table 4 with minor adjustments for the fire in the Isola delle Femmine tunnel, based on Ingason et al. (2015). The average fire duration in the data set is 11 hours, heavily influenced by three extreme outliers: Tauern (15 hours), Mt. Blanc (53 hours) and Nihonzaka (4 days). The median fire duration is 2.5 hours. The total number of fatalities in the fires were 103 people, while 101 people were injured. The high number of fatalities compared to the number of injured illustrate the seriousness of major HGV fires.

Table 4. Data from fires in heavy goods vehicles 1949-1999 (OECD/PIARC, 2001).

Tunnel name	Country	Tunnel length (m)	Date of fire	Cause of fire	Fire duration (hours)	Goods burned	People killed	People injured
Holland	United States	2567	13.05.1949	Goods	4	Carbon bisulphate	0	0
Chesapeake Bay	United States		03.04.1974	Tyre	4	Gasoline	0	1
Caldecott	United States	1083	07.04.1982	Collision	3	33 000 l gasoline	7	2
Isola delle Femmine	Italy	148	18.03.1996	Collision		Gas road tank vehicle	5	34
Tauern	Austria	6400	29.05.1999	Collision	15	Paint	12	0
Frejus	France	12870	05.05.1993	Motor	2	Plastics	0	0
Porte d'Italie	France	425	11.08.1976	Motor	0,75	Polyester	0	0
Moorfleet	Germany	243	31.08.1969	Tyre	2	Polyethylene	0	0
Hovden	Norway	1283	13.06.1993	Collision	2	Polyethylene	0	5
Guadarrama	Spain	2870	14.08.1975	Gearbox	3	Pine resin	0	0
Blue Mountain	United States	1302	1965	Motor		Fish oil	0	0
Pfänder	Austria	6719	10.09.1995	Collision	1	Bread	3	0
Mt Blanc	France	11600	24.03.1999	Motor	53	Margarine, flour	39	0
L'Arme	France	1100	09.09.1986	Collision			3	5
Peccorila Galleria	Italy	662	1983	Collision		Fish	9	20
Serra Ripoli	Italy	442	1993	Collision	3	Paper	4	4
Kajiwara	Japan	740	17.04.1980	Collision	2	Paint	1	0
Nihonzaka	Japan	2045	11.07.1979	Collision	96		7	3
Sakai	Japan	459	15.07.1980	Collision	3		5	5
Velser	Netherlands	768	11.08.1978	Collision	2	Flowers, soft drinks	5	5
Huguenot	South Africa	4000	27.02.1994	Gearbox	1		1	28
Gumefens	Switzerland	343	1987	Collision	2		2	3

Fire duration is a relevant variable if tunnel users are in SWETOs with a limited fire resistance and capacity for breathing air. However, experiences from the Mont Blanc fire in 1999, suggest that people were killed very early in the fire development. Personnel from the French operator, ATMB, were rescued after seven hours in one of the SWETOs. Knowing that people are alive in the tunnel's SWETOs, will affect the emergency response and the resources available on scene to fight the fire before the time runs out. However, we need to analyze the scenarios beforehand and make sure the escalation plans for emergency response exist if a fire should occur.

Commission of the European Communities (2002). Proposal for a Directive of the European Parliament and of the Council on minimum safety requirements for tunnels in the Trans-European Road Network. Brussels, December 30, 2002 (EC-COM, 2003).
By the end of 2002, the European Commission presented the first proposal for a directive on minimum safety requirements for tunnels in the trans-European Road Network (COM/2002/769 final), where the background and objective of the directive was discussed (EC-COM, 2003). The fires in the Mont Blanc and Tauern tunnels in 1999, and the Gotthard tunnel in 2001, were explicitly mentioned as accidents that "have put the risks in tunnels in the spotlight again and call for decisions at political level" (EC-COM, 2003). The primary objective and secondary objectives of the directive was recognizable from UN's expert group in 2001, i.e., primarily prevent critical events, and secondarily reduce the possible consequences of accidents.

According to Thamm (2003), the proposal was discussed within a Council working group during 15 meetings between February and September 2003, when it reached a global position. The Council approved the position October 9th, 2003. In parallel a working group of the European Parliament prepared a report which was accepted in the first reading in Parliament, also October 9th, 2003. Thamm (2003) describes that work was ongoing during the winter 2003/2004 to reach a common agreement between the two documents, which should lead to a decision process that include both activities and a final directive in spring 2004.

Minimum requirements were presented in the Annexes to the proposal, which were published February 4, 2003. On the issue of emergency exits, the proposal was in line with UN's expert group and the final Directive, as it included the requirement that "[s]helters without an exit leading to escape routes to the open shall not be built" (EC-COM, 2003).

3.2 Current European requirements for emergency exits in road tunnels

The approach towards and general understanding of SWETOs was consistently negative in influential work leading towards the final Directive 2004/54/EC. The message is that shelters without an exit leading to escape routes to the open generally represent an unacceptable risk and should not be built anymore. French regulations implemented this type of requirement in 2000 (Circulaire interministérielle n° 2000-63, 2000), the UN's expert group repeated the recommendation in 2001 (UNECE, 2001), it was included in the proposal for the Directive in 2003 (EC-COM, 2003), and finally also included in the Directive in 2004 (EU-directive 2004/54/EC, 2004).

We have not been able to find specific and written documentation in support of the prohibition. However, there were several meetings in 2003, from which documentation and memories still must exist. According to a prominent French stakeholder and actor in the development process of the regulation (Informant 2, 2023), the involved parties during that time (2003) were all convinced, based on the Mont Blanc fire in 1999, that shelters without access was a bad solution and the experts involved cannot remember any dissenting voices. Furthermore, a preparatory document for the first expert meeting, organized by the European Commission (without consultation of the Member States) on 21/5/2002 says "*1.1.1.1 Shelters without an exit leading to escape routes to the open shall not be built*". It was not recalled that anyone ever tried to question this point during all the discussions on the directive in the Council, in the expert meetings, nor in PIARC or elsewhere. Norway did not participate in the discussions in Brussels, as it is not part of the EU. The prohibition was mainly based on the unacceptability of offering users caught in a fire something presented as a safe place, but which might not be safe at all during a large fire. A risk study, considering the Norwegian context, was not performed as part of this decision (Informant 2, 2023).

The background for the evaluation of risk associated with SWETOs is predominately the experiences from the Mont Blanc tunnel fire where two people lost their lives in a shelter. This understanding is reinforced through personal communication with representatives involved with European tunnel safety regulations in the early 2000s.

Table 5 depicts and compares the requirements developed for emergency exits in the proposed and the final Directive. The comparison shows that the final version is clearer in expecting that decisions about emergency exits should be based on a risk assessment associated with fire and smoke spread. It makes a strong connection between smoke management and the means for evacuation. The final Directive is also more stringent than the proposal on requiring emergency exits when AADT exceeds 2000 vehicles per lane. It would be interesting to investigate the foundation for setting the limit at 2000 vehicles per lane.

Table 5. Comparison of requirements to emergency exits in the proposed and final Directive.

Proposal for Directive (2003)	Final Directive (2004)
Section 1.5.1: "Should the smoke extension and spreading velocity under local conditions show that the above-mentioned provisions are insufficient to ensure the safety of road users, additional measures shall be taken, such as the construction of short perpendicular escape galleries to the open or the construction of a parallel safety gallery with cross connections for self-rescue at intervals of less than 500 m." **Section 1.5.2:** "Where there are plans for a tunnel to have a second tube at a later date, an exploration or pilot gallery can be used as an escape route until the second tube is completed." **Section 1.5.3:** "Shelters without an exit leading to escape routes to the open shall not be built." **Section 1.5.4:** "In existing tunnels with bi-directional traffic, emergency exists shall be reassessed by the Safety Officer. A report proposing adaptations of escape routes and ventilation systems shall, where necessary, be transmitted to the Administrative Authority. The Administrative Authority may request additional adaptations."	**Section 2.3.4:** "Shelters without an exit leading to escape routes to the open shall not be built." **Section 2.3.5:** "Emergency exits shall be provided if an analysis of relevant risks, including how far and how quickly smoke travels under local conditions, shows that the ventilation and other safety provisions are insufficient to ensure the safety of road users." **Section 2.3.6:** "In any event, in new tunnels, emergency exits shall be provided where the traffic volume is higher than 2 000 vehicles per lane." **Section 2.3.7:** "In existing tunnels longer than 1 000 m, with a traffic volume higher than 2 000 vehicles per lane, the feasibility and effectiveness of the implementation of new emergency exits shall be evaluated." **Section 2.3.8:** "Where emergency exits are provided, the distance between two emergency exits shall not exceed 500 m." **Section 2.3.9:** "Appropriate means, such as doors, shall be used to prevent smoke and heat from reaching the escape routes behind the emergency exit, so that the tunnel users can safely reach the outside and the emergency services can have access to the tunnel."

It is important to bear in mind that these regulations were adaptations to European contexts. No subsea tunnels nor steep slopes were regarded major issues and clarifications for the knowledge foundations developed. With a passive Norwegian voice, there were no resistance regarding how tunnels could and should be erected to ensure safety in Norway. The consequences have been an idle process with respect to holistic tunnel safety management.

A specific case from Iceland illustrating the current EU approach

The correspondence between ESA and the Icelandic Ministry of Transport and Local Government illustrates EU's interpretation of the requirements. SWETOs was built in the Icelandic Vaðlaheiði tunnel. Since the tunnel was approved after 1 December 2006, the shelters should not have been built without emergency exits leading to escape routes to the open. ESA concludes that this constitutes a breach of point 2.3.4 of Annex I to the Directive. However, they also acknowledge that if the AADT is currently lower than 2000 vehicles per day, the requirement does not apply. This is, however, "only the case if an analysis of relevant risks demonstrates that ventilation and other safety provisions are sufficient to ensure the safety of road users, cf. point 2.3.5. of Annex I to the Directive" (ESA, 2020). In other words, emergency exits should be provided unless a risk assessment comes up with other measures and concludes that the emergency exits are not necessary.

In its response to ESA, the Icelandic Ministry of Transport and Local Government agrees that the SWETOs do not comply with the requirements. They also conclude that "the risk analysis provided by the operator demonstrated that the risk is well within acceptable limits required for tunnels without safety shelters" (MTLG, 2020).

In December 2021, ESA provides a reasoned opinion to Iceland, after investigating written responses and the risk analysis. ESA takes notice that the Icelandic government declares that, based on a ventilation study and a risk analysis that shows that emergency exits are not required, the SWETOs are no longer in use as safety shelters. ESA declares that the "Authority takes note of the evidence provided by Icelandic authorities to demonstrate that safety of the road users is ensured in the Vaðlaheiði tunnel by means of safety measures other than emergency exits, and subsequently of the decision not to equip the tunnel with emergency exits, adopted in accordance with point 2.3.5. of Annex I to the Directive" (ESA, 2021).

It is interesting to notice the weight that ESA places on the risk analysis in this case. ESA makes it clear that "no common methodology for risk analysis has been established under the Directive", which places the responsibility to develop an appropriate method on the EEA EFTA States. However, ESA points to the specific requirements of the Directive and scrutinizes the Icelandic risk analysis against these requirements. Finally, ESA accept the argumentation and takes notes of the evidence provided by the Icelandic Government. Following the correspondence there are currently SWETOs in the Icelandic Vaðlaheiði tunnel which are not operational. This begs the question of who is responsible if tunnel users are injured or killed in a situation where the use of these SWETOs could prevent this?

3.3 Norwegian implementation of Directive 2004/54/EC

The Directive 2004/54/EC is implemented in Norwegian legislation through the Tunnel Safety Regulations (2007) and the Tunnel Safety Regulations for County roads (2015). Requirements herein are generally identical to Directive 2004/54/EC. However, a noteworthy difference is that NPRA, based on an adaptation specified in point 17i of Annex XIII to the EEA Agreement (EFTA, 2023), may approve that emergency exits are not built for tunnels shorter than 10 km and AADT below 4000 vehicles per lane (AADT 8000 in total). The prerequisite is that a risk analysis show that alternative measures provide an equal or higher safety level (MFA, 2006, SD, 2008):

> *"Norway has received approval for the adaptation text on one point. This applies to the requirement for emergency exits (section 2.3.6 in Annex I of the directive). There is a*

> *requirement for emergency exits in new tunnels when the traffic volume exceeds 2,000 vehicles per lane. Norway has been exempted from this if the traffic volume is below 4,000 vehicles per lane in tunnels of less than 10 km. It is a prerequisite that the safety is at least as well safeguarded by alternative measures. This could, for example, be extra lanes, speed reduction, video surveillance and a shorter distance between telephones and fire extinguishers" (SD, 2008).*

Until the latest version of the Norwegian road tunnel design guide (NPRA, 2022), N500 (section 3.6 Emergency exits) did not include the prerequisite about a tunnel-specific risk analysis, while also stating, in section 1.1, that *"Handbook N500 Road tunnels meet the minimum safety requirements in the Tunnel Safety Regulations".* In practice, Norwegian tunnels with AADT < 8000 vehicles have been constructed without emergency exits and without a tunnel-specific risk analysis to identify compensating measures. In 2018, the NPRA conducted a general risk analysis on the topic (Okstad et al., 2018), to compare risk associated with 1) a tunnel with emergency exits, and 2) a tunnel without emergency exits and compensating measures beyond the requirements of N500. In the latest version of N500 (2022), there is no specification about *when* to construct emergency exits, just *how* to construct emergency exits if they are required (N500 section 4.6). Consequently, designers must look to the regulation to identify *when* emergency exits are required.

The evacuation process is affected by the smoke management system in the tunnel. Norwegian practice is the application of longitudinal ventilation in both bi-directional and uni-directional road tunnels. The Directive 2004/54/EC and the Norwegian Tunnel safety regulations specify that in "tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it is acceptable and/or specific measures are taken" (EU-directive 2004/54/EC, 2004).

Potential accident scenarios are largely dependent on the traffic in the tunnel. The self-rescue principle is specifically challenged in situations with major fires (Søvik and Henning, 2015), which is generally associated with heavy goods vehicles and/or transport of dangerous goods. The fundamental position in the Directive 2004/54/EC and the Norwegian tunnel safety regulations, is that transport of dangerous goods is restricted, unless a tunnel-specific risk analysis shows that compensating measures lead to an acceptable risk level. However, Norwegian practice is that no restrictions are implemented on transport of dangerous goods in road tunnels (some exceptions exist), and there is neither a sound practice of conducting tunnel-specific risk analyses concerning scenarios related to transport of dangerous goods. The NSIA's report and safety recommendations following the Skatestraum tunnel fire in 2015 is an illustration of this, which also illustrated the criticality of steep slopes and the tunnel geometry. The most severe scenarios should be part of the risk analyses, and measures should be considered, regardless of a low probability of occurrence. It is an important safety issue to conclude on the dimensioning fire and accident events used to design the emergency preparedness and response system, included the evacuation system. The choice of dimensioning scenarios is a critical process in the systems safety management work. Inadequate risk analyses could lead to situations where the full consequence potential of tunnels is not sufficiently understood and dealt with (NSIA, 2016a). The lack of tunnel-specific risk analyses is also a major issue after the Office of the Auditor General of Norway investigated road tunnel management in 2015-2016 (OAGN, 2016).

4 The Mont Blanc tunnel fire and other influential fires

The fire in the Mont Blanc tunnel is, in addition to the Tauern tunnel and St Gotthard tunnel fires, referred to as the foundation for influential events leading up to the implementation of the Directive 2004/54/EC. The Mont Blanc tunnel fire seems even more important as a foundation for the decision to prohibit shelters without an exit leading to the open. Thus, we include a short description of the Mont Blanc tunnel, as it were in 1999, and the fire. A few other fires where SWETOs were part of the safety system, or relevant to motivate a discussion about SWETOs, are briefly introduced.

4.1 The Mont Blanc tunnel fire disaster

The Mont Blanc tunnel is a 11.6 km single tube tunnel with bi-directional traffic that was opened for traffic in 1965. The tunnel connects the Chamonix valley in France with the Val D'Aoste in Italy. The portal on the French side is located at the end of a 4 km long slope (up to 7 %) at elevation 1 274 m (Duffé and Marec, 1999). HGVs travelling from France to Italy are exposed to high power/energy consumption that is challenging for critical systems that are prone to leakages, high temperatures and sources that might ignite materials.

The traffic volume, measured in 1998, was 5 473 vehicles per day, with a share of 39 % lorries (or HGVs). The tunnel has an upward slope from the French portal towards the highest point of 2.4 % the first 1.9 km and 1.8 % the next 3.9 km. From the highest point, 5.8 km from the French portal, there is a descending slope of 0,25 % towards the Italian portal at elevation 1 381 m (Voeltzel and Dix, 2004). The two driving lanes had a total width of 7 m with a 0.8 m walkway on both sides. Every 300 m there were vehicle rest areas, 3.15 wide by 30 m long. The 36 rest areas were situated on alternating side of the tunnel, starting from number 1 near the French portal to number 36 near the Italian portal. After a serious fire on the 11th of January 1990, 18 SWETOs were installed. The SWETOs were located at every other rest area, i.e., there was around 600 m between each shelter. In the middle of the tunnel there was a switch of the shelter's location from even to odd numbers of rest areas, which means that there was 900 m between the two SWETOs in this area. The SWETOs were supplied with fresh air through ventilation ducts, surrounding constructions had a fire resistance of two hours[3] and the SWETOs were connected by telephone to the control room (Duffé and Marec, 1999).

On the 24th of March 1999 a Belgian HGV loaded with liquid margarine and flour drove into the tunnel from the French side. A fire broke out in the front of the vehicle, and it came to stop near rest area 21 near the middle of the tunnel (6 550 m from the French portal and 5 050 m from the Italian portal). At the time, 29 vehicles (16 HGVs, 9 cars, 1 pick-up van, 1 motorcycle) had entered the tunnel through the French portal. Four HGVs passed the burning HGV, while the other 25 were trapped and later became involved in the fire. Several vehicles also entered through the Italian portal. Small vehicles were able to make U-turns and drove out of the tunnel, while eight HGVs were caught in the fire. A total of 34 vehicles were involved in the fire, of which 20 were HGVs. The fire lasted for 53 hours, and it is estimated that the peak heat release rate was in the area 75 – 100 MW (Voeltzel and Dix, 2004). 39 people lost their lives because of the fire, where 27 were found in their vehicles, 2 in other vehicles, and 9 outside of vehicles. A firefighter died after he was evacuated from the tunnel (Duffé and Marec, 1999).

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[3] We have not seen the design criteria or the analyses of the construction. See section 9.3.1 for a discussion about uncertainties.

The refuge areas in the Mont Blanc tunnel in 1999 were what we may call SWETOs, i.e., there was no evacuation tunnel or gallery parallel to the main tunnel. In the fire investigation report, the SWETOs are highlighted as essential in saving the lives of firefighters and other rescue personnel (Duffé and Marec, 1999, sect. 4.7.3). Lacroix (2001) includes a more detailed description of the use of shelters during the fire:

- Two people, respectively a tunnel user and an employee from the Italian operator (motorcycle patrol), sought refuge a shelter at lay-by 20. Both perished, as it was not possible to arrive with rescue efforts throughout almost the entire 53-hour course of the fire.
- Six people, rescue personnel from French operator (ATMB) led by a professional fireman, sought refuge in a shelter at lay-by 17. All were rescued after more than 7 hours.
- Six people from the public fire service on the French side had to, after several unsuccessful attempts to turn around and drive out, seek refuge in a technical room at lay-by 12. Their fire engine was equipped with breathing equipment for four people, as the incident commander and driver normally do not need such equipment. The incident commander died shortly after evacuation from the tunnel after staying approximately five hours in the technical room. Unlike the shelters, the technical room was not pressurized with fresh air.
- Personnel (unknown number) from a fire engine from the French public fire service had to take refuge in the shelter at lay-by 5.
- Personnel (unknown number) from a fire engine from the Italian public fire service in Courmayeur, together with two firefighters from Aosta, had to take refuge in shelter at lay-by 24. All were rescued after approximately 3 hours.

The number of personnel on the fire engines that drove into the tunnel is not consistently stated by Lacroix (2001), but if we assume that the number was between 4 and 6, we get that between 21 and 25 people were rescued after seeking temporary protection in either a shelter or a technical room. Three people died, two of whom stayed in shelter at lay-by 20 throughout almost the entire 53-hour course of the fire, and one in a technical room at lay-by 12 for approximately five hours. It is not clearly described whether the people in the shelter at lay-by 20 died because of exposure to smoke or high temperature.

The exact technical design of the SWETOs has not been uncovered during this study. However, we know that the SWETOs were marked with a lighted panel above the entrance door, which was hard to identify and recognize for road-users due to the lack of visibility during the fire. Another issue with the design of the SWETOs was that the doors had windows, which gave them the same look as the doors to technical rooms in the tunnel, which do not have the same fire resistance or ventilation (Duffé and Marec, 1999). The tunnel had a transverse ventilation system, where the Italian and French side each controlled a certain part of the tunnel. Around the fire no smoke was extracted, creating a longitudinal flow in this area, providing the fire with oxygen (both through the longitudinal air flow and air supply from the air duct above the burning vehicles) and increasing the smoke volume through mixing/turbulence. This contributed to the fire growth, spread between vehicles, as well as the short time necessary for filling the tunnel with highly toxic smoke, which contributed to the difficulty evacuating the tunnel.

Another problem the investigators raised was that most of the victims did not leave their vehicle. Most of the people who died in the tunnel did not enter a SWETO and died from smoke toxicity (Voeltzel and Dix, 2004). The investigation report argues that based on past experiences during fires in other tunnels (without any reference to which fires) and based on that the people that died in the tunnel did not use any of the SWETOs, it was likely that SWETOs would not be used by tunnel users unless being led there by qualified personnel (Duffé and Marec, 1999).

The investigation report recommends creating a connection between each SWETO and the two tunnel entrances, to create an escape route and a route usable for rescue services. Using the ventilation duct was mentioned as a possibility to achieve this, which also was demonstrated by the fire and rescue personnel during the accident.

4.2 Other influential tunnel fires

The 2001 St. Gotthard tunnel fire

In 2001, the St. Gotthard tunnel facilitated bi-directional traffic tunnel in a main tube. It had a parallel evacuation tunnel, where access galleries between the two tubes were built as shelters, located every 250 m. The shelters were designed so tunnel users could evacuate the main tunnel and wait in these rooms before being rescued through the evacuation tunnel. Henke and Gagliardi (2004) mentioned that nearly all tunnel users close to the fire evacuated safely, either evacuating upstream of the fire or using one of the shelters. One truck driver that died during the fire left one of the shelters and returned to his truck. Another driver that died was found inside the main tunnel several hundred meters downstream of the fire and did not use any of the available shelters. Beard and Carvel (2012) mention that fire fighters used the shelters as a safe starting point to attack the fire.

Some of the findings from the Mont Blanc fire in 1999, were also reported during the fire in the St. Gotthard fire. Henke and Gagliardi (2004) reported that those close to the fire all were aware of the situation, most of them reaching one of the available shelters. Those downstream of the fire, between 300 to 600 m, were not aware of the fire and were surprised. Several died inside their vehicles or did not reach any of the available shelters in time.

(Henke and Gagliardi, 2004) mention that around 30-35 people were evacuated using the shelters. No smoke or heat entered the shelters. However, Beard and Carvel (2012) reported that a door between the tunnel and the shelter closest to the fire did not open due to the high temperatures.

The Swiss government reacted quickly after the fire and developed the *International Fire Academy (IFA)*, located in Balsthal. It is a teaching and testing facility that encompasses other training facilities as well. Firefighters are required to undergo a study program to become a tunnel firefighter. The development of the IFA included detailed studies of the St Gotthard tunnel fire, which include a more detailed narrative of the event than the investigation report, for example with respect to victims' movements in the fire scenario.

The 2005 Frejus tunnel fire

The Frejus tunnel is a 12,9 km single tube tunnel, with bi-directional traffic connecting France and Italy. In June 2005, a fire broke out in a HGV which was transporting tires. Eventually, the fire spread to three other HGVs. Unlike Norwegian tunnels, the Frejus tunnel was monitored 24 hours a day by the French and Italian operating companies. The local preparedness systems included two teams of five to seven safety officers, which were on stand-by to intervene in the event of an incident. Their equipment on each side of the tunnel included a patrol vehicle, a fire vehicle, and an evacuation shuttle vehicle for people.

The tunnel was equipped with eleven ventilated and pressurized shelters. The distance between shelters varied between 615 m-1716 m. The ground surface of the shelters varied between 20-60 m²; all were connected to the fresh air ducts. Before the fire, shelters had been improved with thermal insulation and doors with a 120-minute fire-rating. The shelters had two functions: 1) provide refuge for tunnel users, for a limited time, before being rescued, 2) provide a logistical zone for the rescue services.

The Fréjus tunnel had fire ventilation creating a longitudinal stream from France to Italy. Consequently, several tunnel users on the Italian side were rapidly captured in the smoke. All, except two Slovakian drivers, managed to evacuate the tunnel by themselves or with the assistance of rescue services. The two Slovakian drivers were found dead in the tunnel space. According to the investigation report, none of the shelters were used by the tunnel users that managed to evacuate the tunnel fire. However, the investigators could not be sure that the two perished drivers used one of the shelters. Thick smoke and poor marking were reported as one reason why the shelters were not being used (BEA-TT, 2006).

The shelters seem to have been important during the fire and rescue operation. According to the investigation report, the rescue service used shelters as temporary safe zones before initiating rescue operations in the tunnel, a place to change air tanks, a place to communicate with the operation center (when this was impossible in the tunnel), and a safe retreat and resting area after rescue operations in the tunnel. The rescue service also used the air duct, which was connected to the shelters, to retreat to safer parts of the tunnel, bring in new teams to the fire zone, and support rescue teams across the fire zone (BEA-TT, 2006).

Following the implementation of Directive 2004/54/EC, it was decided, in 2009, to initiate the construction of emergency galleries and 23 new shelters. Currently, the Fréjus tunnel is operated as a uni-directional road tunnel facilitating traffic in two separate tubes (SFTRF, 2023).

The 2011 Oslofjord tunnel fire

The mid-summer 2011 Oslofjord HGV tunnel fire was the first of a several major road tunnel fires occurring in the 2010s. An important response to the fire, was the installation of 25 SWETOs in the tunnel. From the fire investigation (NSIA, 2013) and research associated with the event (Njå and Kuran, 2014) we summarize the following learning points with special relevance to this pre-study. The fire is also discussed in section 7.2.

The transition from "normal conditions" to a challenging situation, due to reduced visibility, was rapid. A queue had developed behind a slow-moving vehicle some distance behind the burning HGV, and major uncertainties amongst the interviewed tunnel users about the reason of the traffic coming to a halt. When the smoke became visible to the people in the queue, the situation developed quickly (Njå and Kuran, 2014).

Some tunnel users decided to stay in their vehicle during the fire. These persons were not part of Njå & Kuran's study. Knowledge about their reasoning and experiences during the event would have been important. However, tunnel users who decided to evacuate were continuously searching for options to improve their situation, e.g., to move away from the fire, by car or by foot (Njå and Kuran, 2014). Evacuees who managed to drive out of the tunnel did so with zero visibility. They were using all three lanes of the tunnel and collided with other vehicles and the tunnel walls. People who were evacuating on foot ran a hazard of being run over by vehicles, and one driver recalls hitting a person at low speed. A group of six people in a vehicle, after picking up five evacuees on foot, had to abandon their attempt to drive out. The group continued evacuation on foot (NSIA, 2013).

Tunnel users who evacuated on foot described difficulties in orienting in the thick smoke. After a while it became difficult to breath and move. Nine people took shelter in two emergency telephone booths. Eight (out of nine) people later took shelter in the space between the tunnel lining and the rock by crawling through inspection hatches in the phone booths. One person remained in the phone booth. The space behind the tunnel lining was less affected by smoke and the air was cooler, even though the space was not designed as a safe area in case of fire. The location of the evacuees was registered by tunnel operators through the numbered phone booths, and they were rescued by emergency responders after approximately two hours (NSIA, 2013).

According to Njå and Kuran (2014), the evacuees who took shelter behind the tunnel lining from phone booth 22, seemed to have identified this possibility themselves. The people in phone booth 16 seemed to have acted upon advice from tunnel operators. Tunnel operators' local knowledge about the space behind the tunnel lining and their ability to make ad-hoc situational assessments, was important for supporting evacuees caught in the smoke. The space behind the tunnel lining had been discussed as part of a debriefing after a fire in the same tunnel three months earlier (Njå and Kuran, 2014).

Evacuees showed group solidarity, which seemed to reinforce the individuals' survival instinct. Conversations, both between the members of the groups and between the group and the tunnel operators, were important contributions to understand their own situation and to deal with their struggle to survive (Njå and Kuran, 2014).

The report by Njå and Kuran (2014) includes a set of statements from the interviewed evacuees, which, amongst other things, questions whether tunnels are designed for realistic emergency situations. They express frustration with the lack of assistance from the tunnel infrastructure, e.g., how evacuation lights were designed, lack of information, inappropriate smoke management strategy, lack of restrictions on traffic, etc. The evacuees' statements are also an important reminder of the major personal trauma it is to experience such events.

The 2017 Oslofjord tunnel fire

In 2017 the SWETOs implemented in the Oslofjord tunnel were used in a real fire, which was also investigated by NSIA (NSIA, 2018). Two HGV drivers entered a SWETO approximately 210 meters downstream from the fire and stayed there for about 40 minutes before being assisted out of the tunnel by the FRS. The following experiences were made after talking to one of the SWETO users (Larsen, 2023):

- The evacuation lights were intuitively understood, i.e., it was clear that one should follow the lights.
- The tunnel user expected to reach the outside when entering the SWETO.
- The air tank in the room was not used.
- The emergency telephone was used for communication both in and out of the SWETO.
- The tunnel user was cold and dissatisfied with the lack of mobile coverage.
- The first aid kit and water were used, as the users sustained minor burn injuries on their hands when operating the SWETO's door handle.

The investigation report mentions that the two truck drivers most likely survived because of the SWETOs (NSIA, 2018), although such a conclusion is associated with considerable uncertainties. Because of communication and video surveillance inside the SWETOs, rescue services had knowledge of the conditions in the SWETO and the location in the tunnel. Rescue services could prioritize extinguishing the fire, after verifying that no tunnel users were inside the tunnel.

The 2013 Gudvanga tunnel fire

August 5th 2013 there was a fire in one of the longest tunnels in Norway, the Gudvanga tunnel. The tunnel is a single tube, bi-directional 11.4 km long road tunnel. The fire started in a HGV driving towards the Aurland portal. Approximately 6 km into the tunnel, the HGV driver noticed a reduction in engine power and 2 km later he had to stop. A fire was under development in the HGV, and it is estimated to reach a peak heat release rate of 25-45 MW. According to NPRA's traffic counting system, there were 58 vehicles in the tunnel at the time of the fire. However, several of the vehicles were able to evacuate early and the owner/driver were not identified by the investigators. For this study, like the Oslofjord fire in 2011, it would have been interesting to understand the decision-making process and actions of all the drivers in the tunnel. However, the fire investigation was primarily concerned with the 67 tunnel users who were trapped by the smoke. Although there are differences between the Oslofjord and the Gudvanga tunnel, the fires in 2011 and 2013 are important to illustrate why SWETOs are important to consider as a measure to improve tunnel users' safety in Norwegian road tunnels. Later, there have been several other fires which adds similar challenges to the discussion (Amundsen, 2017, NSIA, 2015).

Below we have included a set of findings from the fire investigation which are considered relevant to this study. We refer to the NSIA (2015) for details:

- The driver tried to extinguish the fire with a 6 kg portable extinguisher but was unable to prevent escalation, like the Oslofjord 2011 situation.
- The fire was first reported to the central emergency number, 110, by a driver using a mobile phone. Later, several tunnel users called in messages to different emergency centrals, also using their mobile phones. The tunnel's emergency phones were first used 46 minutes after the first call about the fire. Consequently, it was challenging to confirm the fire location in the initial phase.
- TCC was lacking necessary decision support to activate "turn and drive out" signs in the early phase.
- The initial phase of the fire is characterized by uncertainty amongst the tunnel users. Signals that something is out of the ordinary include blinking lights from approaching vehicles, queue, and then a complete stop. Like the situation in Oslofjord 2011, the investigation reports that tunnel users assume the queue is related to some temporary traffic-related issue. Some vehicles in the queue early decides to turn around and leave the tunnel, while others wait.
- The situation develops rapidly when the smoke reaches the tunnel users and there are reports of "chaos, collisions, yelling and panic". The longitudinal smoke ventilation strategy is, like the Oslofjord fire in 2011, contributing to the rapid smoke spread.
- The tunnel users' actions varied. Some stayed in their vehicle, some attempted to drive out of the tunnel, while others attempted to evacuate on foot. Some tunnel users were advised by the medical dispatch center (MDC) to stay in their vehicles and shut down ventilation when they reported difficulties with evacuating the tunnel. Others were advised to attempt driving out of the tunnel.
- Drivers who attempted to drive out of the tunnel had no visibility and the vehicles collided with other vehicles and the tunnel wall, like the Oslofjord 2011 situation. Some vehicles had trailers or camping trailers connected, which made it difficult to turn

around.

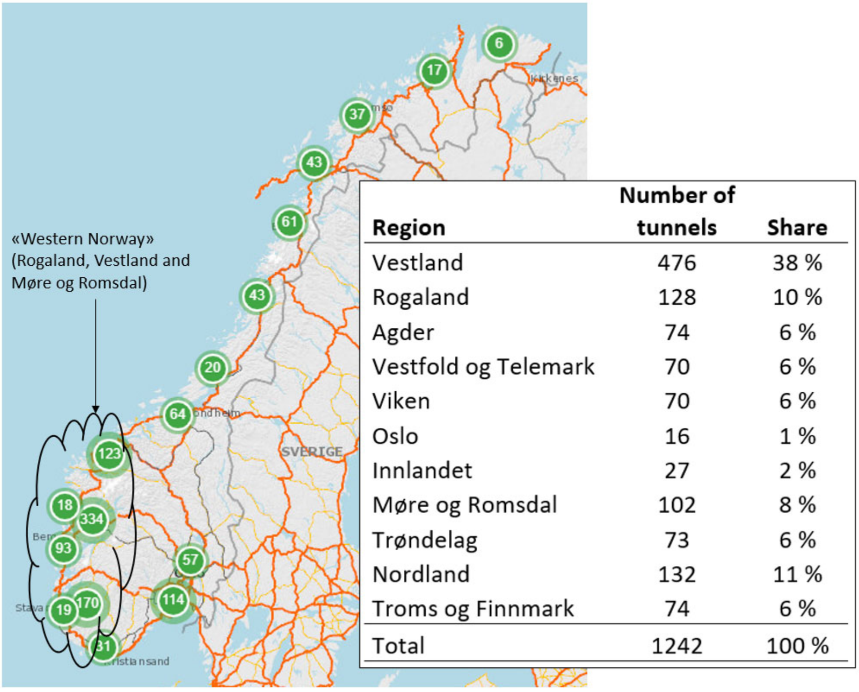
- People evacuating on foot had difficulties orienting in the tunnel and the situation became extreme in many respects. It was difficult to breath, people were hitting the tunnel walls, a family was split, and expectations about emergency response were not met. Following the fire, the victims' express critique about the lack of shelters, lack of compliance with international safety standards, lack of provisions for oxygen, and lack of assistance from emergency responders within the tunnel.

Experiences from the Gudvanga fire in 2013 is also discussed from SINTEF's perspective in section 7.2.

5 The Norwegian road tunnel portfolio

The intention with this section is to gain a broad picture of Norwegian road tunnel characteristics. The information herein is, unless another source is explicitly mentioned, retrieved from the official Norwegian database for road information (NVDB) in January 2022 (NVDB, 2022). We have not conducted any specific quality assurance of the raw data, except removing eight double registrations. Norway is a mountainous and coastal country and the total number of unique road tunnel registrations within NVDB at the time was 1 242.

Figure 3 shows the distribution of Norwegian road tunnels and that they are distributed across the whole country with an especially high density in Western Norway. Many of the tunnels may be characterized as long single-tube constructions with limited traffic volume. Some also have steep gradients. Longitudinal ventilation is the governing fire and smoke ventilation principle. Due to the large number of tunnels, Norway has yet to fulfil its commitment to upgrading all tunnels on the Trans-European Road network (TEN-T) according to the provisions in the EU-directive.



Region	Number of tunnels	Share
Vestland	476	38 %
Rogaland	128	10 %
Agder	74	6 %
Vestfold og Telemark	70	6 %
Viken	70	6 %
Oslo	16	1 %
Innlandet	27	2 %
Møre og Romsdal	102	8 %
Trøndelag	73	6 %
Nordland	132	11 %
Troms og Finnmark	74	6 %
Total	1242	100 %

Figure 3. Geographical distribution of Norwegian road tunnels (source: NVDB 2022)

Road tunnels are crucial for road transportation in Norway, and consequently they have been an important part of the road network for many years. The first edition of the design guide for road tunnels focusing more extensively on tunnel fire safety was issued in 1992 (HB 021 Road Tunnels). Those prior only required tunnel ventilation system to be bi-directional to push the smoke out of the tunnel in the shortest direction (H017 from 1981 and H018 from 1987). In 1991 NPRA assessed road safety in the Norwegian tunnels (Hvoslef, 1991). Even though he points to weaknesses in design and construction of the tunnels, the accident frequency is rather low and fires nearly absent. Since 1992 there has been a major development in society regarding traffic volume, technology, and tunnel safety awareness. Table 6 shows the distribution of opening year for the tunnels registered in NVDB and illustrate the legacy of a road tunnel population built before and during this development.

Table 6. Distribution of the age of Norwegian road tunnels (source: NVDB 2022)

Opening year	Number of tunnels	Share
1900-1939	7	1 %
1940-1949	42	3 %
1950-1959	34	3 %
1960-1969	154	12 %
1970-1979	145	12 %
1980-1989	176	14 %
1990-1999	220	18 %
2000-2009	194	16 %
2010-2019	164	13 %
2020-	34	3 %
Not registered	72	6 %
Total	1242	100 %

Table 7 includes an overview of the registered official length of the Norwegian road tunnels. The longest road tunnel in Norway is currently the Lærdal tunnel, measuring 24 500 meters between its portals. Only one of the six longest road tunnels in Norway, the Ryfylke tunnel is built as a twin-tube tunnel. Norway has more than 500 single-tube tunnels longer than 500 m, of which 98 are longer than 3 000 m (NPRA, 2023b).

Table 7. Length of Norwegian road tunnels (source: NVDB 2022)

Tunnel length	Number of tunnels	Share
< 500 m	605	49 %
500 m - 999 m	226	18 %
1 000 m - 2 499 m	212	17 %
2 500 m - 4 999 m	100	8 %
5 000 m - 9 999 m	35	3 %
> 10 000 m	6 4)	0,5 %
Not registered	58	5 %
Total	1242	100 %

Tunnel class is primarily determined by the tunnel’s annual average daily traffic (AADT) and secondarily its length. A tunnel in class A is intended for low traffic volumes and the technical standard and required safety measures is considerably lower than tunnels in class F. We have not been able to include an overview of tunnels that deviate from requirements in today’s regulations and norms. Nevertheless, to create such an overview would be useful when discussing the need for innovative safety measures, such as SWETOs. Søvik and Henning (2015) suggest that “risk prone” tunnels are single-tube road tunnels with over 12 000 vehicle kilometers/day and longer than 3 kilometers and/or one-lane road tunnels over 1 km with a

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4) Lærdal, Ryfylke, Gudvangen, Folgefonn, Toven and Jondal tunnels

gradient of more than 5 % and/or one-lane road tunnels over 5 km. Njå et al. (2022) developed statistical models of near fires and fully developed fires in Norwegian road tunnels longer than 500 m. They found that slope, length, annual average daily traffic of heavy goods vehicles, and whether a tunnel is subsea are significant factors that increases fire risk. Similar findings are available in Nævestad and Blom (2023), where tunnels with high vertical gradient (slope) is highlighted as especially prone to fire risk. They also point at four subsea road tunnels[5] which stands for 50 % of the near fires and fires in Norwegian high-gradient road tunnels.

From Table 8 we see that most tunnels in Norway are either unclassified due to short length or classified as A or B (N = 936). Tunnel fires were rarely mentioned as a problem prior to the 1990s. The major concern was the intoxicated environment created by vehicles' exhaust in normal operation and how the tunnel owners could ensure the life and injury threatening fumes if people were trapped inside the tunnel. Frøholm (1970) talks about vehicles' natural ability to create a flow of air in the tunnel by dragging in fresh air and push out exhaust air, "sope eksosluft", which also was the concern of European tunnel owners.

Table 8. Norwegian road tunnel's class distribution (source: NVDB 2022)

Tunnel class	Number of tunnels	Share	Comments
A	361	29 %	Usually single tube tunnels with no emergency exits.
B	454	37 %	Usually single tube tunnels with no emergency exits.
C	75	6 %	Usually single tube tunnels. Emergency exits generally required for all tunnels longer than 500 m, but NPRA may grant exceptions when length < 10 000 m and if a risk analysis shows that the same or better overall safety can be obtained with alternative safety measures.
D	45	4 %	Emergency exits generally required for all tunnels longer than 500 m.
E	91	7 %	Double tube
F	20	2 %	Double tube
Not relevant	121	10 %	Unclassified because the tunnel is shorter than 500 m
Not registered	75	6 %	No value included in NVDB
Total	1242	100 %	

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[5] Oslofjord, Byfjord, Bømlafjord and Eiksund tunnels

Restrictions on transport of dangerous goods is not common in Norwegian road tunnels. From Table 9 we see that most tunnels fall within restriction class a, which means no restrictions on transport of dangerous goods.

Table 9. Restrictions on transport of dangerous goods in Norwegian road tunnels (source: NVDB 2022)

Restriction class	**Number of tunnels**	**Share**	**Description**
a	884	71 %	No restrictions on transport of dangerous goods.
b	2	0,2 %	Restrictions on dangerous goods that can cause a major explosion. Includes the Ljoteli and Tysse tunnels.
c	1	0,1 %	Restrictions on dangerous goods that can cause a major explosion, or a major release of toxic gas. This includes the Håklepp tunnel.
d	5	0,4 %	Restrictions on dangerous goods that can cause a major explosion, or a major release of toxic gas, or a major fire. This includes the Ellingsøy, Hammersborg, Hvaler, Valderøy and Vaterland tunnels.
e	0	-	Restrictions on dangerous goods except the following, UN nr. 2919, 3291, 3331, 3373.
Not registered	350	28 %	No value included in NVDB.
Total	1242	100 %	

From a strict statistical viewpoint, there are minor number of tunnels that would qualify for considering SWETOs. These are defined by their subsea characteristics, operational conditions (for example being part of ferry transport sections), HGV AADT, length, and slope. This could be a reasonable starting point to address costs and practical changes, safety performances etc.

6 SWETOs as an element in the evacuation system

In this section we present a brief system description of existing and planned SWETOs in Norwegian road tunnels. SWETOs have been in operation in the Oslofjord tunnel for a decade, while new SWETOs are under construction in the Flekkerøy and Frøya tunnels. Finally, we include results from some areas of application for shelters in other sectors/industries.

6.1 SWETOs in the Oslofjord tunnel

The Oslofjord sub-sea tunnel is in Viken county and is a part of the TEN-T road E 134. The tunnel is approximately 7 300 m long and has a maximum vertical gradient of 7 %. In 2022 the average annual daily traffic (AADT) was 10 442 vehicles, 16 % long vehicles.

As a measure to improve the safety of tunnel users in case of major fires, the NPRA decided to build 25 SWETOs in the Oslofjord tunnel after a major fire in 2011. The SWETOs were considered and approved as a temporary measure, while planning a permanent solution with a second tunnel tube (NPRA, 2012). The SWETOs were constructed using existing blasted niches/cavities in the tunnel. A fire rated wall of 300 mm constructed with lightweight expanded clay aggregate (LECA)[6] and an interlock space is separating the tunnel space from the SWETO space. The fire rated walls towards the tunnel space and the interlock have fire rated doors, class A120. Some specified design criteria were:

- 0,4 m^2 floor area pr person.
- < 20 000 ppm CO_2 is defined as the limit of incapacitation.
- 14 vol% O_2 is defined as the limit of incapacitation.
- Smoke: 375 g min/m^3 leads to incapacitation.
- 40 °C for until 3 hours and 60 °C for until 1.5 hours.

The design fire is based on the Runehamar test tunnel fire experiments conducted during the UPTUN project (Ingason and Lönnermark, 2003). The most severe fire reached a peak heat release rate of 203 MW and represented an energy corresponding to 247 GJ. The duration of the fire was approximately 1 hour, which included the cooling phase. It is assumed that the design fire reaches a heat release rate of 3 MW after 4 minutes and its peak value of 200 MW within 15 minutes after initiation. The total fire load is 500 GJ, which corresponds to an HGV with approximately 20 tons of combustible load. When calculating the fire exposure, it is assumed that the room is located 100 m downstream from the fire.

Calculations are basis for designing the fire protection between the tunnel and the shelter. The models are developed by the consultancy company responsible for design and verified against the Runehamar experiments results. The calculations include a set of assumptions about, e.g., fire growth rate, (lack of) fire spread between vehicles, fire location relative to shelter, smoke production, human tolerability limits and human behavior during accidents. Uncertainty is not addressed explicitly, but it is assumed that the calculations are on the conservative side, i.e., that the calculation results are worse than reality[7]. The calculations show that heat is not considered a major challenge. In fact, the rooms may be rather cold. The most critical design criterion is associated with smoke exposure, which could result from leakages in the constructions (mainly doors). To prevent smoke from spreading to the room there is a water lock on the drainage system.

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[6] Any compact LECA wall with thickness > 150 mm will normally correspond to a fire resistance of at least EI 240, i.e., four hours (Saint-Gobain, 2023).

[7] Working with conservative numbers, assumptions etc in risk analyses or other probability-based studies confuses and brings a message to convince the reader. It should be avoided.

The exposed rock inside the SWETOs is considered essential in the design, as moisture generated by occupants will condensate on the cold surface. This contributes to reduce the relative humidity when there are many people in the room.

The rooms are equipped with camera with detection, an emergency phone (two-way communication), a first aid kit and water. There is a continuous evacuation lighting system that leads tunnel users towards the SWETOs and a green light frame around the door. In the tunnel space, outside the SWETO, there is a lamp that indicate if the room is in use. Most rooms (20 out of 25) are equipped with breathing air containers, which are manually operated by the tunnel users. The system is designed to release the air over a period of 3.5 hours. The five rooms that do not have any additional breathing air containers, are considered large enough (> 180 m^3) to provide sufficient air supply for at least three hours.

After operating the SWETOs for more than ten years, no particular maintenance challenges are reported, either from operating staff, electrical operators or TCC operators. In general, the environment in the SWETOs is better than the tunnel space. While air quality is the major issue in the tunnel space, humidity is the most critical issue in the SWETOs. To improve this matter, the inner door is kept open by magnet to increase air circulation. There is no coverage for emergency communication nor mobile phones in the SWETOs, which is a challenge for emergency responders (and the shelter's users). We have not interviewed the operation and maintenance contractor; thus we don't know the availability, reliability and capacity of the SWETOs during the operational period.

The construction of the second tunnel tube for the Oslofjord tunnel is currently expected to start during 2024 (NPRA, 2023a). When the new tube is completed, the tunnel will facilitate uni-directional traffic in two separate tubes. Evacuation in case of emergencies will be facilitated through interconnections between the tubes.

6.2 SWETOs in the Frøya tunnel

The Frøya tunnel was opened in year 2000 and is a sub-sea connection between the islands Frøya and Hitra in Trøndelag County. The population of Frøya has varied over the years, but due to growth in the aquaculture industry the population have grown since its minimum in 1990. Currently there are approximately 5 000 inhabitants on the island. Frøya is Norway's biggest municipality in terms of fish farming, and the local industry is connected to fisheries, fish reception and fish processing. Fresh products from Frøya are in demand in large parts of the world, which calls for a stable transportation route to the mainland Norway. The Frøya tunnel is 5 300 meter long and had an AADT of 2 157 vehicles in 2022, where 15 % (ca. 320 vehicles pr day) were long vehicles. The tunnel is considered steep (maximum 10 % vertical gradient) and tight (tunnel profile T8).

Trøndelag County Council is in the process of upgrading the Frøya tunnel in accordance with the Tunnel Safety Regulations. Measures to improve conditions for self-rescue is considered necessary. SWETOs are suggested as a solution. The planning and construction of SWETOs in the Frøya tunnel is regarded a pilot project by the Norwegian Roads Directorate. The purpose of the SWETOs is to provide road users in the tunnel with a room that is protected against heat and smoke, has sufficient air, that one can go to if self-rescue on foot or by vehicle cannot be carried out.

The SWETOs in the Frøya tunnel are based on those installed in the Oslofjord tunnel. They are constructed as caverns. A membrane intended for water protection is installed in the caverns. The membrane is in light grey color and will constitute walls and roof in the SWETO. There is a fire protected wall separating the tunnel space from the shelter cavern, with a minimum fire resistance of EI180, i.e., three hours fire resistance using the standard ISO 834 time-temperature curve. An interlock space is separating the tunnel space and the main area of the SWETO, which means there are two doors between the SWETOs main space and the tunnel.

The tunnel will be provided with 12 SWETOs, where the distance will be between 340 m and 500 m. The SWETOs are designed for maximum 50 people. This is based on a dimensioning person density of maximum 0.6 m^2 pr person, which gives a minimum floor area of 30 m^2. There are benches for 10 people, first aid equipment, fire blankets, food, and water. Continuous evacuation lights in the tunnel, and a green light frame around the shelter's doors will guide tunnel users towards the SWETOs.

All rooms are equipped with pressurized air tanks that provides fresh air and create an over-pressure compared with the tunnel space. Air supply is sufficient for 50 people for three hours. Tanks are operated manually with a simple open/close valve. The valve is pre-programmed to release the air evenly over a period of four hours.

An emergency station, identical to those used in the tunnel, is located on the wall in the SWETOs main space. The station has a telephone to communicate with the TCC and a loudspeaker, which allows the TCC to talk directly to people in the room without lifting the phone. It is also possible to operate the loudspeaker from the emergency response cabinets located outside of each portal. There is the possibility of speaking to a single room or all rooms at the same time. There is a camera in the inner corner of the room, which allows the TCC and emergency responders to keep track of people and behavior in the room. The camera is connected to the AID system, which allows automatic detection of movement.

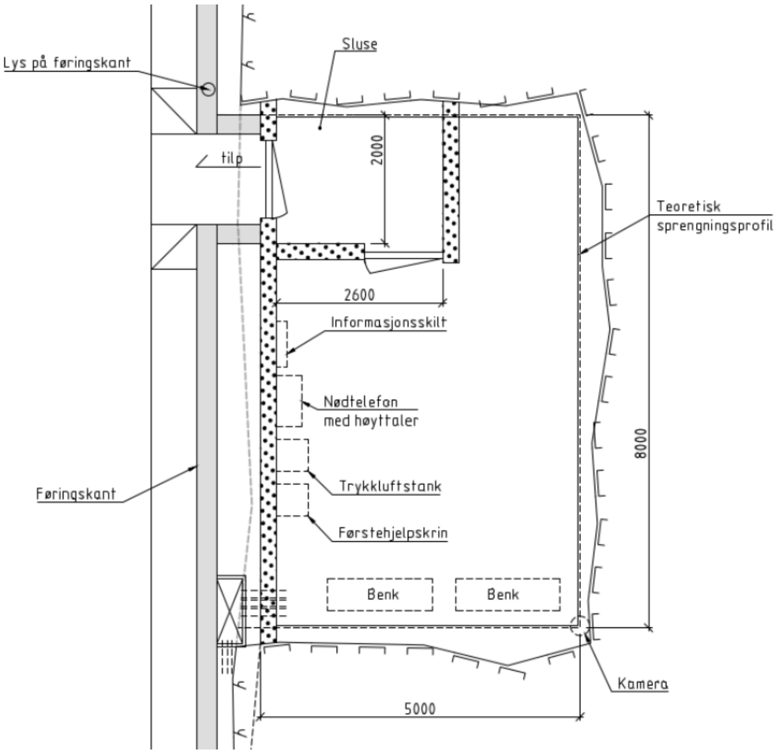

Figure 4. SWETO design in the Frøya tunnel (Norwegian terms).

The SWETOs are connected to the upgraded and fire protected main power supply in the tunnel, which provide a basic protection against power outage. In addition, the equipment associated with the SWETO system is connected to the tunnel's emergency power system. All equipment connected to the emergency power is served by an uninterrupted power supply (UPS) unit for minimum three hours.

Tunnel users will find written information at an information board on the wall. The written message is repeated in Norwegian, English, German, and Polish languages.

Both doors in the SWETO have sensors that provide a signal to the SCADA system when they are operated. The rooms are normally dark, but lighting in the room and a lamp (to indicate to emergency responders that the room is in use) on the wall in the tunnel space is automatically switched on when doors are operated and/or movement is detected by the camera. The lights are on for five hours after being switched on. The TCC is also able to control lighting through the SCADA system. The emergency station in the SWETO has the same function as an emergency station in the tunnel, which means an alarm is given when opening the door and when removing a fire extinguisher.

6.3 SWETOs in the Flekkerøy tunnel

In 1989 a sub-sea connection was established between the island of Flekkerøy and the mainland, southwest of Kristiansand in Agder county. The island is part of Kristiansand municipality.

The Flekkerøy tunnel is part of county road Fv 457 and is currently being upgraded to comply with tunnel safety regulations for county roads. In 2022 the AADT in the tunnel was 4 904 vehicles, 7 % long vehicles (NVDB, 2022). The tunnel is steep, with a 10 % decent from both portals towards the lowest point 100 meters below sea level.

Three SWETOs are installed to improve the safety of tunnel users, especially pedestrians and cyclists, in case of fire. The tunnel is 2 320 m long and the distance from each portal to the first SWETO is 650 m. The third SWETO is located between these two rooms, which means that the distance between the three rooms is approximately 500 m. The SWETOs are supplemented by continuous evacuation light (LED stripe designed as a handrail) and the "Evacsound" system to guide tunnel users towards the portals or the SWETOs, depending on the fire's location relative to a SWETO. Evacsound allows for two-way communication between TCC operators and tunnel users and provides sound signals designed to lead people towards the portal or SWETO. To signify the location of the SWETOs, there is a green light frame around the doors. The light frame is continuously lit in normal operation and will blink when the fire procedure is activated.

Unlike the SWETOs in Oslofjord and Frøya tunnels, the SWETOs in the Flekkerøy tunnel is a concept consisting of an air-pressurized container located in a fire protected niche. The niche is separated from the tunnel space with a fire-rated LECA wall, minimum fire resistance REI 120-M. In practice, a LECA-wall with a thickness > 15 cm will have a fire resistance of at least REI 240. The air-pressurized container is located 5 m from the fire wall and constructed with fire resistance EI60. The container has an interlock space with gas tight doors and an automatic flush system designed to prevent polluted air leaking from the interlock to the seating space.

Each container is dimensioned with seats and compressed breathing air for 12 people for at least six hours. The air supply is automatically activated when the door is opened unless the container is set to "maintenance mode". The container has a toilet, first aid equipment, drinking water and food. The container has a camera that gives an overview of the seating area. A calling system in the container provides communication with the TCC. The system is activated when the container door is opened, which allows two-way communication. It is also possible to communicate with the containers from the emergency panels located outside each portal. The communication system has redundant cabling from both portals.

The temperature inside the main space of the container should not exceed 26 °C during the six hours of fire exposure. A consultant company has conducted CFD simulations using different fire sizes, i.e., 100 MW, 200 MW and 400 MW to investigate the fire exposure (Rambøll, 2022). The conclusion from the simulations is that a 100 MW fire produces the most critical exposure. It is argued that lack of oxygen and the major soot production leads to a strangulation of the more severe fires. However, experiences from the Skatestraum fire (NSIA, 2016a) and hand calculations shows that a fire may grow considerably larger than 100 MW before being ventilation-controlled in a road tunnel of this geometry. Nevertheless, the maximum temperature may not be severely affected by the fire growing beyond 100 MW, as the flame reaches the ceiling, and the maximum ceiling temperature is effectively the maximum flame temperature, cf. section 7.4 and Ingason et al. (2015).

In agreement with the local FRS a cabinet with six cylinders with compressed air for breathing apparatus are installed in the fire protected cavern. The cylinders are intended as backup air for the FRS's personnel.

6.4 Shelters used in other industries

"Shelter in place", "safe havens", "rescue shelters" etc. is common in several industries, for instance:

- Protection against toxic gas releases in the process industries (South et al., 1993, Gandhi and Sarrack, 2016, Mannan and Kilpatrick, 2000).
- Protection against dam disasters (Mamat et al., 2019).
- Protection against adverse events in tunnels under construction (ITA, 2018, NFF, 2021).
- Protection against natural disasters (Pierce and West, 2017).
- Protection against adverse events in the mining industry (DMP, 2013, Zhan et al., 2012, Margolis et al., 2011, Zhang et al., 2019, Zhang et al., 2014).
- Protection against fires in buildings, using the defend or protect in place strategy (Proulx, 1999, Kulkarni and Agashe, 2017).

Jenssen et al. (2017) provides a review of use of shelters in other sectors, where they find that shelters contributed to saving 22 lives in the period 2007-2017.

Shelter in place strategies in industry and residential buildings

South et al. (1993) discuss the risk associated with sulfur, H2S, gas release on oil & gas fields, contrasting two evacuation strategies: evacuation versus *shelter in place* (SIP). In this study the SIP strategy is implemented on people living nearby the process plant, i.e., the shelters are the people's homes and/or offices. Examples are provided, where the SIP strategy have saved lives. For instance, the ammonia spill from a tanker truck where nearby vehicles were used as shelters, the ammonia spill from the derailment of a railroad tanker where houses nearby functioned as shelters, and the sulfur trioxide release where people survived inside their homes and people outside where injured. Similar arguments are carried to the forefront by Mannan and Kilpatrick (2000). The authors of the two papers argues that SIP is an appropriate strategy in some cases, which should be considered by emergency responders. The characteristics of these cases is that it is safer to stay in place than trying to evacuate. Similar situations and consequence considerations are equally relevant to fires and toxic releases in a road tunnel: *Evacuation through smoke is potentially lethal and should be avoided.*

Proulx (1999) investigates occupant response during a high-rise building fire. It is concluded that the vulnerability of occupants increases if the evacuation is delayed. At some point of the fire development, she concludes that it is probably safer to instruct occupants to stay in their apartments and protect in place, unless the occupants are in immediate danger. Staying in the apartment was a less complex strategy, and which meant that the occupants that chose this strategy did not have to cope with encountering smoke and anxious neighbors.

"Bomb" and hurricane shelters

Shelters designed to protect populations from nuclear weapons are remnants from the Cold War era (FEMA, 2006). The shelter is a temporary place of safety, designed to protect its occupants while the extraordinary loads are present. It has been a while since new bomb shelters was designed and constructed in Norway. In the US, FEMA (2006) has developed a design guide for shelters and safe rooms in case of CBRE (chemical, biological, radioactive, and explosive) threats, which also includes design guides for tornado and hurricane shelters. While some design criteria will depend on the specific hazard, others are more universal and included here.

The available floor area in a shelter should reflect the duration of the occupancy, which is dependent on the type of event it is designed for. For tornado shelters (typically two hours occupancy time), FEMA recommend a minimum floor area as low as 0,46 m^2/person, while hurricane shelters (up to 36 hours occupancy time) should have a floor area of at least 1 m^2/person. For short-term occupancy shelters, such as tornado shelters, FEMA recommends the following minimum floor areas based on special needs:

- 5 square feet (0.46 m^2) per person adults standing.
- 6 square feet (0.56 m^2) per person adults seated.
- 5 square feet (0.46 m^2) per person children.
- 10 square feet (0.93 m^2) per person wheelchair users.
- 30 square feet (2.79 m^2) per person bedridden.

The headroom in a shelter should be at least 2 meters and there should be at least 1.8 m^3 of net volume per shelter occupant. To allow for appropriate breathing air, it is necessary to limit the amount of CO_2 in the atmosphere. FEMA recommends a maximum level of 0.25 %, although normal healthy persons tolerate 0.5 % and nuclear submarines operate with a level of 1 % CO_2 in the atmosphere. For a sedentary man a provision of 85 liters per minute of fresh air will maintain a CO_2 concentration 0.5 %. To maintain a level of 0.25 % the amount of fresh air should be 142 liters per minute. In addition, FEMA highlights the importance of lighting to reduce agitation and stress, emergency power supply for the expected occupancy time, route marking for wayfinding and obvious signage.

Refuge chambers for tunnels under construction

The International Tunnelling and Underground Space Association's guideline (ITA, 2018) includes recommended minimum requirements for refuge chambers in tunnels under construction. Some of the recommendations are listed below to compare with FEMA's requirements:

- Capacity: To be determined based on a project specific risk assessment, but at least the number of workers and visitors and considerations regarding shift change.
- Dimensions: At least 0.5 m^2/person floor area, 1.5 m head room and a volume of 0.75 m^3/person.
- Occupancy duration: At least 24 hours.
- Positive overpressure: At least 100 Pa, and less than 1 kPa. Should be monitored and indicated to occupants.
- Equipment: Lighting, seating, storage space for rescue equipment, toilet, drinking water, fire extinguisher, first aid kit and atmospheric monitoring.
- Inspection and maintenance: functional tests, periodical checks, visual inspection for internal cleanliness, checks/service by manufacturer, replacement of consumables etc.
- Instruction and training: operating instructions (appropriate languages), periodic training, exercises, records of training etc.

Implications for road tunnels

Shelters to protect occupants from temporary accidental loads are common in several societal sectors. The basic idea is to use the shelter when this is considered safer than to evacuate or when evacuation is impossible. The protect-in-place strategy does not guarantee the safety of its occupants. Uncertainties will always exist: the accidental load might be larger than expected, the construction may have unknown weaknesses, or the users might be unaware of the shelter's functionality. A decision to apply a protect in place strategy or not should build on a careful consideration of the available alternatives and the associated uncertainties.

7 Current knowledge base for SWETOs

The partners of this collaborative study, notably the NPRA, UiS/IRIS, SINTEF, and RISE, have conducted and/or initiated research relevant for self-rescue and SWETOs. Findings from this research represents the knowledge base that we bring into this study, and which will affect the related activities, such as the workshop and the updated literature study, cf. section 8. While representing an important background for the study, and affecting methodological considerations, the knowledge is important. Hence, a short summary of relevant research from the collaborating partners is presented in this section. The summary from RISE is included in full in Appendix A.

7.1 Research initiated by the NPRA

NPRA initiated their own investigations and studies on self-rescue following the major fires since 2011 and were responsible for initiating research studies by others. See for instance the summary of SINTEF's research activities in section 7.2.

In the report about the "five major tunnel fires", NPRA lists several learning points for future studies and considerations (Amundsen, 2017):

- Self-rescue is challenging in long and steep road tunnels, and it is important to discuss what prerequisites are required to maintain the self-rescue principle. Assisted evacuation should also be part of the discussion.
- The Norwegian principle for fire and smoke ventilation involves predefining the direction of ventilation in cooperation with the local FRS. The major fires have illustrated that there are challenges with predefining the direction and opportunities associated with a more context-dependent smoke management strategy.
- Communication between emergency responders have been challenging. It is recommended that local FRS becomes acquainted with the tunnels in their area.
- There is a major potential to learn from previous fires but statistics of fires and injuries in road tunnels is incomplete. The situation is improving.
- The healthcare system is responsible for follow-up of the injured from road tunnel fires, which means that long-term consequences are unknown to the NPRA. There is generally lack of knowledge about human tolerability to heat and smoke exposure and it is probable that the victims' long-term psychological effects are underestimated.
- There is a potential associated with improving emergency preparedness through preparedness analyses, which target prerequisites for successful self-evacuation processes, and dynamic emergency response plans.
- There is rapid development in technology that could provide real-time data from road tunnels, which could serve as decision support for emergency response.
- SWETOs might be an appropriate safety measure in long single-tube and steep road tunnels. More knowledge is needed about whether tunnel users will find and use the rooms, how the rooms should be equipped and what to be dimensioning loads.
- There is a need to develop a risk-based decision support model (DSM) with the aim of recommending appropriate safety measures dependent on a tunnel's characteristics. The DSM should also consider the need for restrictions on dangerous goods transport.

The literature study by Frantzich et al. (2016a) on evacuation and technical safety measures to support evacuation in road tunnels with bi-directional traffic is important. The study collects information about theories on human response in tunnel accidents. It highlights *the phase model* (detection & alarm, recognition, and response phase) and associated information about how to interfere with the phases, i.e., to diminish the time spent in each phase. The study indicates that the evacuation system needs a holistic design, which means that the evacuation system must be assessed with the entire safety management of the tunnel. All the parts of the evacuation system need to "work in the same direction" to reinforce the value of information, speed up decision making and reassure tunnel users that they have made an appropriate decision. Examples of sub-systems and factors that need to work together (Frantzich et al., 2016a):

- The importance of early detection and alarm is emphasized, but there are specific difficulties associated with sound in tunnels (background noise and echo). "New technology", such as in-car systems and apps on mobile phones could improve alert and recognition. Apps could impact different phases (interpretation and response), but there are some challenges, such as information about usage, foreign users etc. The authors concluded that the literature is scarce about the potential of new technology for tunnel safety.
- Traffic information signs (TIS) and variable message signs (VMS) are well-known technologies in existing tunnels. Potential improvements include better adaption of the content of such equipment in accordance with how tunnel users perceive and interpret the information. This entails the design of messages, color of signs and other equipment, design of symbols etc.
- Human behavior in accident situations is an important topic. Several actions are inevitable in case of an emergency. Some will act fast and seek an exit, while others will stay and observe the development of the incident. Social influence includes copying the behavior of others, which is both a challenge and a solution depending on the initial action. Recognition of risk varies between tunnel users who are intimate with the fire, and those who are far away (cannot see smoke). Different information solutions may be needed to activate a desired response. Maximizing the benefits of different safety equipment in a tunnel prerequisite a fundamental understanding of human behavior and the adoption of a human-centered design approach.
- Environmental signs affect human decision making in a tunnel accident. For instance, smoke spread is a threat to tunnel users, but also an indicator that something is out of the ordinary in the tunnel. Seeing smoke is, however, not necessarily enough to spur immediate action. A combination of indicators that provides a consistent message that something is wrong is necessary to reach a higher confidence that tunnel users will act appropriately. An example of the opposite is the unfortunate event of changing the conditions for tunnel users after a decision is made, e.g., by changing wind direction after an evacuation has been initiated.
- During the response phase, the speed of evacuation is an important variable. Using the vehicle to evacuate would be preferrable, but evacuation on foot may be necessary if a tunnel user is unable to use the vehicle. Walking speed in evacuation situations depend on individual characteristics and the situation. In smoke-filled situations it is found that the walking speed is in the area 0.2 – 0.9 m/s, compared to a general walking speed without smoke of 0.65 – 1.9 m/s. Further, it is stated that the walking speed in experiments is largely dependent on visibility, and less dependent on slope, surface, age, gender, or the persons height. When the visibility is low people tend to use their hands to feel their way and avoid collisions with obstacles, which support measures that people can hold on to, e.g., handrails. In real evacuation situations, where the distance to an exit may be very long, the slope might influence walking speed. The amount of work performed when walking in a 10 % slope is three times larger than walking on a flat surface. The aging population and increased bodyweight, also adds to the uncertainty associated with existing data on walking speed and capacity.

Frantzich et al. (2016a) suggest SWETOs as a measure to improve the safety of tunnel users during evacuation from fires. The primary strategy should be to evacuate the tunnel through its exits. If the primary strategy fails, the SWETOs could serve as a secondary option, and a temporary safe place. The distance to a SWETO should be indicated on both tunnel walls. The authors discuss the design and placement of signs, and how standardization would be beneficial to improve recognition effects. Light and sound (signals and/or spoken messages) contributes to make tunnel users aware of and reinforce prompt evacuation.

7.2 Findings from recent SINTEF research projects

This sub-section is a short summary of SINTEF's research in the last decade with important findings regarding SWETOs and related topics i.e., self-rescue, wayfinding, emergency exit signs and systems. The text is an edited version of Dr. Gunnar D. Jenssen's input to this pre-study and represents Jenssen's perspective. The research involves testing of promising new technologies and systems developed in the last 25 years.

An important outset for SINTEF's work regarding SWETOs is the following conclusion from the post Mont Blanc tunnel fire investigation (Duffé and Marec, 1999): *"Road users in tunnel fires will not seek emergency exits if not guided by personnel"*. To understand if this is the case or not, it is necessary to both look at the use and design of the rooms themselves, and the use of SWETOs in a holistic context, as part of a total safety concept. The French critique was related to heat resistance and smoke entering SWETOs during the fire. In the years passed since the Mont Blanc tunnel fire there has been considerable technological innovation on wayfinding systems, knowledge about self-rescue, and the design of safe shelters.

The focus in SINTEF's research reported here has been testing novel and promising technology and systems for safe egress and wayfinding to shelters as well as the design, functionality, and minimum necessary inventory of such rooms. Part of this research has been gathering experiences from human behavior in real tunnel fires with and without SWETOs.

As a starting point for the research the NPRA in cooperation with SINTEF proposed that SWETOs should be easy to find (even in smoke) and accessed by all road users (universal design principle). In addition, the rooms need to serve its purpose; heat resistant, functional, trustworthy, and acceptable to stay in for a longer time-period. This implies that the role of shelters in the self-rescue process must be examined and validated as safe and secure. Hence research on how to alert, inform and guide road users safely to the nearest shelter in a tunnel hazard incident is highly relevant. The survivability of the shelters and tunnels-users perception and accept staying over time in a tunnel fire has also been a major topic in the research.

7.2.1 Research activities and results

Following the **Oslofjord tunnel fire in 2011**, SINTEF was, together with Safetec, involved in conducting a post-accident risk analysis (Safetec, 2011). The study included interviews with 33 survivors who had been trapped in the smoke. Evacuees searched for doors and huddled together, 6-7 people, in phone booths and behind tunnel wall lining. One person was hit by a car attempting to drive out. Most cars did not manage to turn and drive out. The fire brigade had trouble entering the tunnel due to stranded cars. ATVs with trailers were purchased as part of search and rescue team bringing oxygen masks in to assist stranded tunnel users and drive them out between the cars partly blocking the tunnel.

Following the **Gudvanga tunnel fire in 2013**, SINTEF assisted (2013-2014) the Norwegian Safety Investigation Authority (NSIA) in the post fire investigations. The work consisted of an in-situ investigation and interviews with 67 survivors; fire fighters, hospital staff, ambulance crew and heli-doctor. Evacuation behavior was a major issue in the study. Seven cars (12 %) managed to pass the fire and drive out of the tunnel at an early stage. 32 cars (56 %) managed to turn around and drive out while the visibility still was good. 18 vehicles (32 %), which included 17 cars and one bus and a total of 67 tunnel users, were trapped in the smoke. Of the 67 people, nine (13 %) left their vehicle to evacuate on foot or tried to drive out. 58 (86 %) chose to stay in their vehicle, many in a mental freeze state with lack of control of bodily functions.

The tunnel users who decided to evacuate on foot stumbled slowly 8.4 km towards the portal for two hours. The tunnel walls were used as guidance. Some entered stranded vehicles but left when the environment became too warm. During the evacuation people searched for doors and exits but there were none. Only a few evacuees used the emergency phones in the tunnel, but most of them used their mobile phones to talk with relatives and next of kin. Some said farewell, while others did not mention their critical situation.

All the 67 tunnel users were sent to hospital with smoke injuries. 50 % of them had PTSD symptoms one year after the incident. The study points to a family who managed to drive out of the tunnel after it was filled with smoke. Family members were given specific tasks to follow up during the evacuation process, e.g., to comfort dog, give water and warn when near tunnel wall. This family experienced some control in the situation and developed no PTSD symptoms in the aftermath.

As part of a revision of US highway tunnel safety guidelines, SINTEF was involved in a project on **emergency exit signs and marking systems for highway tunnels**. The project was a joint effort between Texas Transportation (PI), Gannet Flemming and SINTEF. The aim was to determine effective messages for encouraging drivers to leave their vehicles and evacuate a tunnel on foot; determining sign and marking formats that most effectively lead people to emergency tunnel exits; and determining the most visible sign and marking materials and technologies for use in highway tunnel environments. Focus group interviews were conducted to explore potential evacuation messages and delivery methods. Next, a simulated tunnel environment was used to test driver responses to emergency messages, and to test visibility and comprehension of selected emergency exit signs and markings, including the running man pictogram prescribed in the International Organization for Standardization, ISO 7010.

Results indicate that the running man pictogram was correctly or partially understood as indicating an exit by most participants, and that a directional sign with the pictogram, "EXIT" text, a directional arrow, and distance in feet was correctly understood by virtually all participants. Internally illuminated signs were visible at somewhat longer distances than photoluminescent signs; visibility for all sign technologies dropped sharply when viewed through smoke. Some of the findings from the study (Higgings et al., 2015a, Higgings et al., 2015b):

- To alert tunnel users and make them act quickly, the tunnel users need to know:
    - What is happening? e.g., "fire in tunnel".
    - What should I do? e.g., "walk to exits".
- Visual messages on variable message signs (VMS) and voice messages are highly effective in alerting tunnel users and affecting desired evacuation behavior.
- Acoustic beacons above emergency exits strengthened desired evacuation by emergency exit doors.

- White and green LED has superior visibility in smoke over photoluminescent signs.
- 81 % acted upon VMS signs, 73 % upon audible speech messages. Only 20 % left the car with no messages.
- "Travelling" lights that indicated a direction were preferred as pathway markings compared with unison flashing lights. The audio beacon became a preferred option to indicate the location of a doorway.
- LED signs were visible in thick smoke at 4 m while photoluminescent only at 1.5 m.

In 2014-2015, SINTEF conducted a **study on self-rescue and use of SWETOs** for the NPRA (Jenssen et al., 2017). The literature review conclude that the primary issue individuals face when staying in underground rooms is a pervasive sense of danger and entrapment. Prolonged stays underground exacerbate problems related to feelings of isolation and monotony. Understanding factors contributing to undesirable feelings is crucial. Feelings of isolation and monotony are associated with a lack of windows, clear exits, limited visibility, and connection to the outside world. Concerns about fire, water leakage, and structural collapse are frequently cited as worries. Even during shorter stays, rooms below ground level are often perceived as cramped and oppressive. Visible pipes and the presence of mold and dust contribute significantly to a negative basement-like atmosphere. Additionally, the absence of visual variation and the inability to see green plants and trees contribute to feelings of monotony. Difficulties associated with staying in underground rooms can potentially lead to anxiety, stress, fatigue, impaired judgment, or aggression.

Studies demonstrate that the implementation of a blue light window on the ceiling, creating an illusion of an outdoor sky view, can significantly enhance the sense of space beyond the actual physical dimensions. Successful applications of illusions in underground military facilities involve using curtains in front of window frames to create a sense of reassurance that there is a window and an exit, even when situated 40 meters underground with only a rock wall or concrete behind the curtain. Brightly lit rooms can create the illusion of a tunnel opening or an outdoor experience.

Consequently, measures that mitigate adverse aspects of stays in underground rooms become more critical. Important design aspects to impact safety and perceived comfort during stays in underground rooms include:

- the design of the entry zone,
- perceived ceiling height,
- lighting,
- air flow, and
- communication with the outside world

If self-rescue shall work the tunnel must be designed and equipped with technical installations that will aid and support road users in an emergency. Examples of measures that will strengthen the ability to self-rescue are; the use of automatic incident detection to ensure the detection and alerting tunnel users of fire early; and the use of continuous escape lights (handrail with white LED) along the tunnel wall. In 2018-2019, SINTEF conducted a study funded by NPRA on **measures to facilitate wayfinding to shelters** (Jenssen et al., 2018). The project was a cooperation between SINTEF, Lund University and DNV and included a Virtual Reality (VR) study comprising 109 subjects from eight nations. Different smoke densities (visibility levels) were tested and results for registered for behavior, walking speed and walking route. The subjects were also interviewed.

The study shows that all subjects find shelters in thick black smoke with a very low visibility (0.5 m sight distance). In the scenario, the subjects were aided by visual and acoustic egress systems, i.e., continuous static white LED handrail mounted 1 m up on wall and loudspeaker beacons above exit doors with speech message "exit here". Without wayfinding systems tunnel users follow the center line until obscured by smoke and randomly follow either tunnel wall. Some even turn around and walk towards the fire. People walk more slowly using four times more time to find exits if they find them.

Following the concerns about user acceptancy of shelters, SINTEF conducted a study about **design of shelters, acceptance, and trust** (Jenssen et al., 2020). The study included five different SWETO designs, which were tested in SINTEF's ISO-certified climate lab combined with VR-technology. 44 participants took part in the study. Good lighting and communication with tunnel operators are key factors increasing feeling of safety, security, trust, and acceptance of rooms. Placement of speakerphone is important. All but one tunnel user found water, blanket, first aid, call screen, and helped persons in distress. No one attempted to leave.

Shelters are well-known technology used in other high-risk sectors, such as the petrochemical industry and the oil and gas industry. Overall, the SINTEF studies show that road users can find shelters in smoky tunnel environment, feel safe when staying in such shelters and accept to stay there in high temperature and humidity, provided it has the right design and equipment. Theories and previous studies on human behavior in confined underground spaces indicate people can become aggressive and selfish in emergencies or in confined spaces. Evidence from real tunnel fires and the SINTEF VR studies reported here show that people are much more altruistic and helpful, based on previous underground studies as well as the self-preservation theory. The Virtual Reality simulations have also shown that people follow the instructions from the Road Traffic Control Centre (tunnel operator), help others and find first aid even in poor light. Perceived safety is highest in shelter design with good lighting and an illusion of blue sky and perceived extra ceiling height in critical situations. The studies show that minimum requirement to equipment in shelters for people to feel safe, secure and preserve dignity are:

- Communication system (two-way) with the outside world (tunnel operator)
- Water and food
- First aid equipment
- Toilet
- Something to divert focus (e.g. books, games for children, wi-fi for mobile phones)

Something that diverts the focus helps mitigate possible post-traumatic stress syndrome (PTSD). In addition, shelters must be smoke free by excess air pressure, heat resistant to extreme fires (200-300 MW) have reserve oxygen for at least 1 hour and, if possible, continuous air supply of fresh air from above ground.

7.2.2 Identified knowledge gaps and suggestions for further studies

Based on the studies and experiences described in the previous section, Jenssen presents the following knowledge gaps and suggestions for further studies.

Currently, there does not exist functional requirements associated with SWETOs. Without functional requirements it is challenging to develop appropriate technical solutions and management systems, as the purpose of the safety measure is not clearly stated. It is rather clear that SWETOs are intended as a last resort-measure in major tunnel accidents, especially major fires. However, it is not clear what principles we should adopt regarding the rooms' capacity for people, requirements about spacing between rooms, design loads etc. The task of developing appropriate functional requirements for SWETOs is important to guide decisions about future designs, but also in the process of developing alternative designs which may be exposed to testing, modeling, and risk analyses.

Table 10. SINTEF's perception of available studies and knowledge gaps associated with relevant issues and human behavior in tunnel accidents.

ISSUES AND BEHAVIOR	STUDIES	METHOD	TUNNEL TYPE	GAPS
Driving out	Very few	Mostly driving simulator studies and a few full scale	Mostly one way twin tube	None in on-off ramps in large junctions, and narrow long tunnels
Walking (Walking, walking speeds, social influence, egocentric or altruistic behavior)	Many	Mostly modelling	Road, Rail, Metro	Scarcely in tunnels with steep gradient With disabled, elderly, children
Evacuation room design and acceptance	Very few	VR Study	Sub Sea Single tube 7km long	Very few from road tunnels Use in real fires Under real stress
Freeze-panic (Panic, fear, anxiety stress and navigation in smoke, freeze response, influence of smoke, information processing, decision support)	Scarce	Mostly based on real fires	Mostly one way twin tube	Very few from road tunnels
Way-finding Tech-systems (Emergency exit signs and systems, effect of technical installations including alarms, lighting)	Many	All types	Twin tube	New measures
C-ITS In-Vehicle (Effect of in-car C-ITS messages to assist evacuation in early phase while entering tunnel, or stopped inside with fire in sight or not)	Very few	Driving simulators	Motorway	Closed tunnel Decision to act

Previous studies have filled former evident knowledge gaps on evacuation in tunnels. However:

1. Most research has focused on a specific part of evacuation, e.g., effect of visual or acoustic guidance with flashing lights or voice messages;
   a) rarely the whole evacuation process, and;
   b) rarely in a full-scale tunnel or based on real tunnel fires.
2. Most experiments, both full scale and in VR, are conducted with white smoke and fairly good visibility. In real fires thick black smoke fill the whole tunnel. Smoke layering only occurs near the fire in an early phase or in tunnels with transverse ventilation (extraction).
3. When trapped in thick black smoke, at best offering an arm's length of visibility

(70 cm) it is very difficult to walk fast. In addition, real smoke affects people physically by reducing lung capacity and psychologically by increasing fear, anxiety, and stress. It can also be quite toxic affecting brain function and loss of vision due to eye irritation.

We cannot transfer and predict behavior from normal tunnels to yield new types of tunnels, e.g., steep, narrow, high altitude, high heat, flammable construction (noise frost insulation).

Table 11. Methods used in studies of shelters self-rescue, wayfinding, validity, and constraints.

METHODOLOGY	STUDIES	VALIDITY	Constraints
1) Real tunnel fires	Very few	Very High	Too few Limited to the type of tunnel (i.e., Mont Blanc, Oslofjord, during tunnel construction)
2) Full -scale experiments	Few	Quite high	Costly Access to tunnels
3) Modelling	Many	Low	Unrealistic conditions and behavior
4) Down scaled Lab-experiments	Many	Low	Unrealistic conditions and behavior
5) VR studies	Few	High	Validity and realism vary with type of 3D models and VR technology

We need more systematic post-fire studies from real fires in different types of tunnels. Post fire investigation should include interviews of survivors and fire & rescue services. We cannot predict the evacuation behavior and use of shelters based on behavior under normal conditions in tunnels or a limited type of shelters. It is also hard to infer to special tunnels, for example very narrow tunnels, two-layer tunnels with staircase, tunnels with high gradient, tunnels with long on-off ramps, tunnels with different ventilation, etc. What if ventilation fails, lighting or wayfinding systems due to sloppy maintenance or refurbishment?

Based on previous SINTEF research, the following topics are suggested for further studies:

a) Appropriate distance between shelters.
b) Shelter design and acceptance, e.g., cross cultural studies validating main results of SINTEF studies where this was not included.
c) Walking speed in steep tunnels with children, elderly, disabled etc.
d) Self-rescue by driving out, for example different driver's ability to turn their vehicle in a road tunnel, depending on cross section and visibility.
e) Self-rescue in long narrow on-off ramps in motorway tunnels.
f) Effect of tunnel safety training, education, and tunnel safety campaigns.

7.3 Findings from recent research projects at UiS/SEROS and IRIS

This chapter is a short summary of SEROS and IRIS' knowledge generating activities on tunnel safety deemed important for the discussion about SWETOs. The text is an edited version of Professor Ove Njå's summary of research on self-evacuation and SWETOs in road tunnels and thus represents the original author's perspective.

Following the Oslofjord tunnel fire on 23 June 2011 an in-depth analysis of the fire was conducted (Njå, 2016, Njå and Kuran, 2014). The analysis gave interesting perspectives from the actors involved in the rescue work. These findings could be summarized:

- 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.
- 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 of 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' post traumas and stresses is underrated.

Knowledge about the contents of goods travelling through Norwegian tunnels is scarce, especially about 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.

SWETOs are part of the answers to all these aspects, considering the wide specter of Norwegian tunnels with potential for self-rescue situations that do not offer sufficient systems for obtaining self-rescue. There are several entities that need to be further explored and scrutinized to fully understand the potential performance of SWETOs. These are; capabilities of road-users, condition and damage potentials of vehicles travelling through tunnels, availability of and interaction between safety systems in tunnels, co-operation between first responders, tunnel owners/administrators and road traffic centers in emergencies, and how safety management of tunnels are currently conducted.

Road-users as assets

Bjørnsen and Knapstad (2017) studied fresh driving licensees and the focus on safe travelling through tunnels as part of the education program. The study revealed huge variation amongst the road-users' competencies, and that experiences were strongly associated with tunnel fire risk perception. Tunnel fire risk perception is regarded a major challenge for the planning of educational programs that should ensure that future license holders reflect upon potential fire and accident scenarios in tunnels. The researchers also found gender differences in the competencies and response behaviors, in which women were more prone to passive behavior in case of fires.

Knapstad is currently reporting from several studies on road-users learning processes. These works are either in review processes or being currently finalized for publication in scientific journals. She has tested an information campaign and found that it has promising learning potential, but the long-term learning is dependent on the road-users investing time and opportunities to reflect on scenarios and potential self-rescue behavior. As part of the phd-study she has investigated the digitalized VR-technological approaches to learning and found that learning is rarely part of the technology development. A closer collaboration between pedagogical experts and ICT-developers is needed, which might improve the performances of self-rescue and SWETOs.

Conditions of and damage potential of vehicles through tunnels

Since SEROS/IRIS started working on tunnel safety studies, there have been very little research activities studying the operational conditions and traffic loads in tunnels. Risk analysis processes, though positively perceived (Njå et al., 2013), rarely assess or gather knowledge that emphasizes physical, mechanical, and chemical characteristics. Current NPRA-managed data gathering is related to counting numbers, in which there are indication of technical failures or other causes to the fire incident, nothing further. The NSIA studies have often detailed information about the scenarios and fires, but is rarely concerned with the conditions before the accident occurs and the vehicles and traffic as such. The Skatestraum tunnel accident investigation is an exception (NSIA, 2016a), but we have not seen scientific studies on conditions related to vehicles and traffic flows. Njå (2019) initiated such perspectives in his master thesis, but there are knowledge gaps to address to understand how road-users might be exposed to dangerous situations in tunnels and their need for SWETOs. Ingason emphasizes the importance of physical knowledge related to tunnel fires, but their research group are neither not occupied with fire accident conditions. Christian Kuran studies rule bending in the commercial HGV-transport (Kuran et al., 2022, Kuran et al., 2023), which is relevant when addressing proneness and damage potentials of HGVs. Kuran's studies reveal extensive rule bending behaviors in the industry, defined as adaptive non-conform behavior.

SWETOs and interaction between safety systems in tunnels

SWETOs will be part of the evacuation system which is part of the safety systems that comprises the holistic safety of the tunnel. UiS has addressed the issue of systems thinking as a premise for understanding the tunnel safety in several studies (Bjelland et al., 2021, Bjelland et al., 2015, Time and Njå, 2017). This is also the perspective of the work UiS did to assess the feasibility of Evacuation-rooms in tunnels (Njå, 2017a). The study used a counterfactual approach to demonstrate the performance of shelters in investigated tunnel fires. The conclusion was that shelters were regarded highly feasible and effective. Distances between shelters must be carefully considered, but a distance > 500 m would be difficult to defend based on the self-rescue principle. The report recommended a stepwise introduction and implementation of shelters. The report also questions the lack of using experience data from other high-risk industries and sectors in the assessment of the feasibility of the shelters.

University of Stavanger is currently running the Tunnel safety Study program (Njå, 2023). This study program encompasses personnel working in various fields of tunnel safety, and discussions about the self-rescue principle has been prominent. The conclusion from the discussion so far is that something must be done to improve the situation for the tunnel-users. A recurrent theme is that emergency preparedness analyses and emergency response arrangements are too much developed as aid for the first responders rather than seeing the needs for the tunnel users.

Co-operation between first responders, tunnel owners/administrators and road traffic management

Since 2012 the competence situation in tunnel fire safety for the first responders has been on the agenda (Bjørnsen et al., 2023a, Bjørnsen et al., 2019, Bjørnsen et al., 2023b, Bjørnsen and Njå, 2020, Njå and Svela, 2018, Svela and Njå, 2017). The findings are numerous, but the important features related to SWETO considerations are the huge variation in competencies, the lack of knowledge for example related to the specific tunnels and their fire safety strategies, and the lack of systematic coursework and training options to improve the situation. The co-operation principle plays a major role in Norwegian fire and rescue work, but the interaction between parties can be significantly improved. SWETOs can influence the way these actors' approach self-rescue.

Safety management of tunnels - practices

Safety management practices within engineering in the construction and tunneling industry has been the major issue in several studies the past decade (Bjelland, 2013, Bjelland and Aven, 2013, Bjelland and Njå, 2022, Bjelland et al., 2021, Bjelland et al., 2015, Borg et al., 2014). A key finding is that practitioners are struggling with important concepts associated with performance-based engineering, such as risk and uncertainty. Risk studies are undertaken as a verification task, rather than as an activity to support the design and operation activities. As a result, safety management becomes reactive, both during the phases of design and operation. Standards and norms, which specifies acceptable solutions, are fundamental for the understanding of a "safety level". A changing world, which calls for innovation and flexibility to deal with emerging threats, is not compatible with reactive safety management. As a response, a transition towards principles based on systems thinking, performance-based design and active safety management is suggested. These principles acknowledge that safety is a control task, which is undertaken by the actors of the socio-technical systems. The task involves active management towards the systems' safety goals. Uncertainty is an important concept since we are dealing with future states and consequences of operating complex systems.

7.4 Fire dynamics of vehicle fires in road tunnels

This section is an extract from a memo written by Dr. Jonatan Gehandler and professor Haukur Ingason at RISE Fire Research, Sweden, as an input to this pre-study. The text represents the original authors' perspective. The full memo is found as Appendix A.

7.4.1 Vehicle fires, heat release rate and fire spread

Vehicle fires in tunnels differ from vehicle fires in the open. The main difference is the influence of natural or mechanical ventilation flow as well as the geometry and type of surrounding enclosures such as walls and ceilings.

Deflection of the flame by forced ventilation is an important factor for fire development in the vehicle and fire spread to other vehicles. For instance, if there is a fire in the engine compartment of a HGV, and the wind blows in the direction from the driver cabin, the fire will probably not grow further and the total HRR is limited to 2-5 MW. On the other hand, if the wind blows in the direction towards the front of the driver cabin the risk for fire spread towards the trailer behind it increases considerably. If it spreads the HRR can vary from 30 – 200 MW, depending on the cover of the trailer unit, the amount of combustibles inside the trailer and the length of the trailer (Ingason et al., 2015). The time to reach a peak HRR varies from 8 – 18 minutes.

The fire size from Dangerous Goods Vehicles (DGV) is in the order of up to 400 MW, e.g., the petrol tank fire in the Skatestraum tunnel in 2015 in Norway (NSIA, 2016a). The time duration could be shorter, but the level of heat flux is enormous. The gas temperature in the vicinity of the fire in the Skatestraum tunnel was estimated to about 1365 °C. It corresponds with heat fluxes around 390 kW/m^2, which is the highest that can be measured in tunnel fires (Ingason et al., 2015). There are also cases where the total HRR from multiple HGVs involved in the fire has become as high as for a single DGV. In the Mont Blanc fire, the maximum HRR was estimated in the range of 300 - 380 MW with 15 HGVs involved, the Tauern tunnel fire was estimated to be in the range of 300 – 400 MW and 16 HGVs involved. In the St Gotthard tunnel fire, the maximum HRR was estimated to be 100 – 400 MW and 13 HGVs involved (Ingason et al., 2015, Lundström, 2023). This shows the potential of the maximum HRR when multiple HGVs become involved in the fire during the incident. The ventilation conditions did not limit these fires. It is not possible to add single HGVs and sum up the HRR. The time aspect of the fire spread and fuel consumption for each HGV needs to be considered (Ingason et al., 2015).

In tunnel fires with forced ventilation the likelihood for an under-ventilated fire is low. The upper HRR limit can easily be estimated with knowledge of geometry and ventilation rate (Ingason et al., 2015). With cross-sectional area between 50 m^2 and 100 m^2, and velocity of 2.5 m/s or more, the maximum heat release rate that is required before getting ventilation controlled is between 400 MW to 800 MW, respectively, see eq. (2.20) in (Ingason et al., 2015).

In a conventional powered bus, the fire usually starts in the engine compartment in the rear end of the bus. The engine compartment is fire protected and, in many cases, there is an extinguishing system installed. The risk of fire spread is not very high for most buses, but if the fire spread to the passenger cabin there will be several factors that determine the fire development, comparable to a compartment fire in a building. Depending on the length and width of the bus, and if it is double decker or not, the HRRs will become around 25 – 50 MW. The number of performed fire tests for buses is less than 5 in the world. The measured time to reach a peak HRR has been found to vary from 7 – 14 minutes. The highest measured HRR in buses is 34 MW, but estimation show that it can be higher (Ingason et al., 2015).

A single passenger car is usually limited to 2-8 MW, and up to three passenger cars around 8 – 16 MW. The time to obtain peak HRR varies between 8 – 55 minutes (see fig. 2 in Ingason et al., 2015). The mechanism of the fire development is similar to fires in a HGV driver cabin or a passenger bus. The access to flammable material such as seats, interior and exterior plastics material in combination with access to oxygen are vital in this process.

The driving forces in fire spread between burning vehicles in tunnels is the HRR of the first burning vehicle, the wind velocity and the tunnel width and height, where the tunnel height is more important than the width. In HGV fires, it has been measured that up to 70 – 100 m downstream a second HGV could start to burn[8] (Lönnermark and Ingason, 2006).

The total released energy in different types of vehicles varies. For HGVs that have been used in fire test it varies from 10-240 GJ. In buses it varies between 41-44 GJ and in internal combustion engine vehicles (ICEVs) between 2.1 – 8 GJ (Ingason et al., 2015).

7.4.2 New energy carriers

New energy carriers can be classified into liquid form, gas form or batteries (Gehandler et al., 2016, Lönnermark, 2010).

Vehicle gas storages are protected by a pressure relief device (PRD) that, e.g., in the event of fire, should release the gas before the container ruptures. Vehicle fuel safety is regulated by the United Nations Economic Commission for Europe (UNECE). For instance, CNG vehicles are regulated by UNECE R110 where a bonfire test should be conducted to ensure that the tank does not burst in the event of fire. Despite this, pressure vessel explosions have occurred

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[8] During the Mont Blanc event, the fire spread to vehicles 290 meters from the initial fire. However, there are uncertainties associated with the mechanisms of fires spread (Duffé & Marec, 1999).

without the thermal melt-fuse released (TPRD) (Lowell, 2013). One reason for this has been attributed to local fire exposure of composite tanks that do not reach the TPRD. This has been verified in field tests (Gehandler and Lönnermark, 2019). Explosion incidents has also occurred for LPG vehicles (Lönnermark, 2010). These incidents have led to more stringent requirements (UNECE R134 and GTR[9] 13) for hydrogen vehicles (Ehrhart et al., 2020, Scheffler et al., 2011) including a local fire test and innovative explosion-free composite tank design (Cirrone et al., 2019).

Finally, electric vehicles (EV) refer to vehicles that make use of traction batteries such as lithium-ion batteries for their propulsion. Although EV fires often end up in the media, such fires are rare, about 5 to 20 times less probable than a fire in a ICEV (Willstrand et al., 2020). EV fires that start in the traction battery are exceptionally rare. However, it should be noted that statistics so far are scarce and that the share of old EVs is much lower than the share of old ICEVs.

The total energy contained in the fuel does not differ widely between different types of vehicles. For most light vehicles it will be in the order of 1 – 2 GJ. Therefore, many vehicle fires will look the same regardless of the fuel. What can differ with different fuels is how fast or slow the energy is released, which is very dependent on the fire scenario. For most vehicle fire scenarios, liquid fuels, may start, or will contribute earlier. Gas fuels are more safely stored but can burn faster and even result in an explosion. Batteries are difficult to ignite and can burn for longer time. For loaded HGVs the impact from the energy carrier has an even smaller share of the total energy content. However, an increased use of alternative fuels, such as hydrogen, would imply an increased transportation of such fuels by DGV, which also need to be considered, although the long-term viable transport solution for hydrogen is by pipeline (Pritchard and Rattigan, 2010).

Fires in electric vehicles could last longer and are more difficult to extinguish. However, if the battery becomes involved (i.e., thermal runaway), and is not extinguished, it will burn out completely within a few hours or less. Then the battery contains no energy and cannot re-ignite. Initially there was great concern with hydrogen fluoride (HF) being produced from battery fires (and vehicle fires in general). From an evacuation perspective there are several acute toxic gases present regardless of the type of vehicle burning, e.g., CO, HF, HCl and SO_2 (Willstrand et al., 2020). From a rescue service perspective HF from battery fires has been shown to be a minor problem since their personal protective equipment offers good protection against HF (Wingfors et al., 2021). Fires in gas vehicles inside tunnels are more problematic from a rescue service point of view. The Swedish civil contingency agency (MSB) have issued guidelines stating that 40 m or more upstream and downstream of a fire exposed gas tank is considered a prohibited area (MSB, 2022). This means that the rescue service, with the current means, will not manage to make an offensive intervention, but will need to await that the gas vehicle burns out and then wait to ensure the tank is either empty or has been cooled and regained its strength before they can approach the vehicle. Such a defensive approach will take longer time to carry through, several hours or more.

7.4.3 Tunnel fire dynamics

The main focus of tunnel ventilation research is on critical velocity and backlayering lengths. Critical velocity is the ventilation velocity needed to prevent backlayering in the tunnel, and is dependent on the tunnel geometry (height, width, slope), the fuel's height above the ground,

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[9] Global Technical Regulations

and the heat release rate. The critical velocity depends highly on tunnel height, and up to a certain size the heat release rate and may vary between 2.5 m/s up to 4 m/s. When the heat release rate exceeds a certain value and depending on the tunnel height, it no longer influences the critical velocity. With a tunnel height between 5-7 m, the corresponding values are 10 MW and 20 MW, respectively. This means that most tunnels in Scandinavia obtain critical velocity at 3 m/s and 3.6 m/s, respectively.

Backlayering length is important as that the rescue services need to get access to the fire from the upstream side, and therefore the amount of backlayering needs to be limited. For example, a passenger car (5 MW) burning in a 5 m high tunnel and 2 m/s ventilation will obtain 38 m backlayering length. This means that the rescue service can expect some heat flux from the smoke in the ceiling towards them when attacking the fire. The critical heat flux for fire fighters is often said to be 5 kW/m^2. This can be calculated when the backlayering length is known.

It is not always optimal to achieve the longitudinal critical ventilation velocity in tunnel fires. On the downstream side there are many things that can occur compared to if ventilation is limited. Imagine that there is almost no wind inside the tunnel. The hot gases from the fire rise towards the ceiling and after hitting the ceiling they spread in both directions along the tunnel. Due to the buoyancy of the hot smoke layer the smoke gas layer starts to propagate slowly along the ceiling. At a given distance the smoke has cooled down so much that the smoke gas layer descends to the level where road users are escaping from the fire. In the case of no ventilation this will occur on both sides, and depending on the heat release rate this distance can vary up to several hundreds of meters. If fire ventilation is started, this distance will be shortened considerably on the upstream side of the fire, and on the downstream side the turbulent smoke gas layer is mixed with the air down to floor level and may affect escaping people. Initial fire ventilation must consider the conditions of evacuees. The smoke layer height and the gas temperature in combination with the toxic gas concentration dictates the tenability.

In the case when the fires become very large there is a risk that the fire spread between vehicles. The best example of this situation is the Mont Blanc and the Tauern tunnel fire with many HGVs involved. The flame length can be easily calculated by correlations developed in (Ingason et al., 2015). For example, a 100 MW HGV fire in a tunnel with a longitudinal ventilation of 2 m/s and 5 m height and 10 m width will have a flame length of 17 m downstream the fire. This means that a second vehicle within 17 m downstream the fire will ignite. The smoke backlayering will for the same situation be 55 m, so the situation on both sides of the fire is quite challenging for the fire rescue services.

7.4.4 Fixed firefighting systems (FFFS) and tunnel fires

The use of FFFS in the EU and US has historically been difficult for tunnels. Until around 2010 very little or no acceptance from authorities was experienced. The main reason was tests carried out in the Ofenegg tunnel in 1965 in Switzerland. These tests had a major impact on the use of FFFS in Europe. The main reason were some adverse secondary effects in the vicinity of the fire. The visibility was reduced, and the gasoline fuel reignited (hot spot far away) after the system had extinguished the fire and a deflagration occurred. Later research has shown that the adverse effects are difficult to obtain and today FFFS are more or less accepted in most countries. In Sweden all new major road tunnels will be equipped with FFFS and some older tunnel will be refurbished with FFFS to increase the fire safety.

One of the advantages with FFFS is that there is a possibility to make trade-offs with other technical systems. Example of such trade-off is to reduce the fire protection of the construction. Also, the heat release rate is reduced and the risk for evacuees is decreased, especially in the case of HGVs or DGVs. The ventilation strategy can be made easier using FFFS, i.e., the system makes the fire less sensitive to higher ventilation rates, and it can even dilute the toxic conditions downstream the fire (Ingason and Li, 2014).

One important feature of FFFS is that it can effectively cool down the surface temperature of structures. Sprinklers are sometimes used to re-classify products by installing spray sprinkler heads that cool the exposed surface of products such as glazed windows. The water spray is an effective surface cooler and could be very effective in colling the surface temperature of a wall construction exposed to heat fluxes from large fires. Lundqvist (1991) and Göras et al. (2001) has measured the cooling effects of fire wall products to find the optimized water flow hitting the wall on the non-exposed side. The water spray from sprinklers is something that can be used and investigated as a potential measure to reduce the risk with thermal heat flux to doors or walls adjacent to evacuation shelters.

7.4.5 Thermal impact on shelters: an example

The fire development for different vehicles varies but single vehicles seldom burn for longer than one hour (Ingason et al., 2015). If there is a situation such as in the Mont Blanc tunnel fire, with multiple HGVs vehicles involved, the incident heat flux towards the wall will be felt not only from the fire beside the shelter but also from the other vehicles burning at the same time but further away. If most HGVs burn for about one hour, the most intensive incident heat flux will be during the time the vehicle beside is burning. The fire will continue towards other vehicles but the contribution towards the wall will be reduced as the fire travels away from the wall. The next shelter, depending on the distance between the shelters, will eventually start to experience heat flux towards the wall.

Figure 5 presents the results of a calculation of 20, 50 and 100 MW fires' thermal impacts on a hypothetical shelter at different distances. Readers are directed to Appendix A for calculation assumptions and equations. It is clear from Figure 5 that the maximum heat flux towards the fire wall (adjacent to the shelters inside the blasted space in the mountain), decay rapidly as a function of the distance from the fire. The incident heat flux is a maximum value as the gas temperature used to calculate the heat flux is the maximum ceiling temperature, and the gas temperature at lower levels is lower. Based on the assumptions, the incident heat flux is reduced to 10 % or more of the maximum value 100 m from the fire. The velocity influences the stratification of the smoke. Increased stratification means that the high gas temperature and incident heat flux are mainly on the upper part of the door or walls to the evacuation shelter, while the lower part of the door or walls to an evacuation shelter is not directly exposed to such high gas temperatures as explained above, and the temperature is at a much lower level, which may be more like ambient temperature. As the distance increases, say 10 times the tunnel height or more, the smoke stratification starts to decay and the gas temperature at the ceiling become more similar to the rest of the cross-section at about 50 – 100 times the tunnel height. This is a rough estimation but gives a reasonable description of the conditions in a tunnel with ventilation, say 2 m/s or less. Higher velocity tends to destroy the smoke stratification earlier than with low velocity. Thus, Figure 5 gives a reasonable estimate of the incident heat flux as a function of the distance. This incident heat flux can be used to calculate the wall or door temperatures in an evacuation shelter as a function of time.

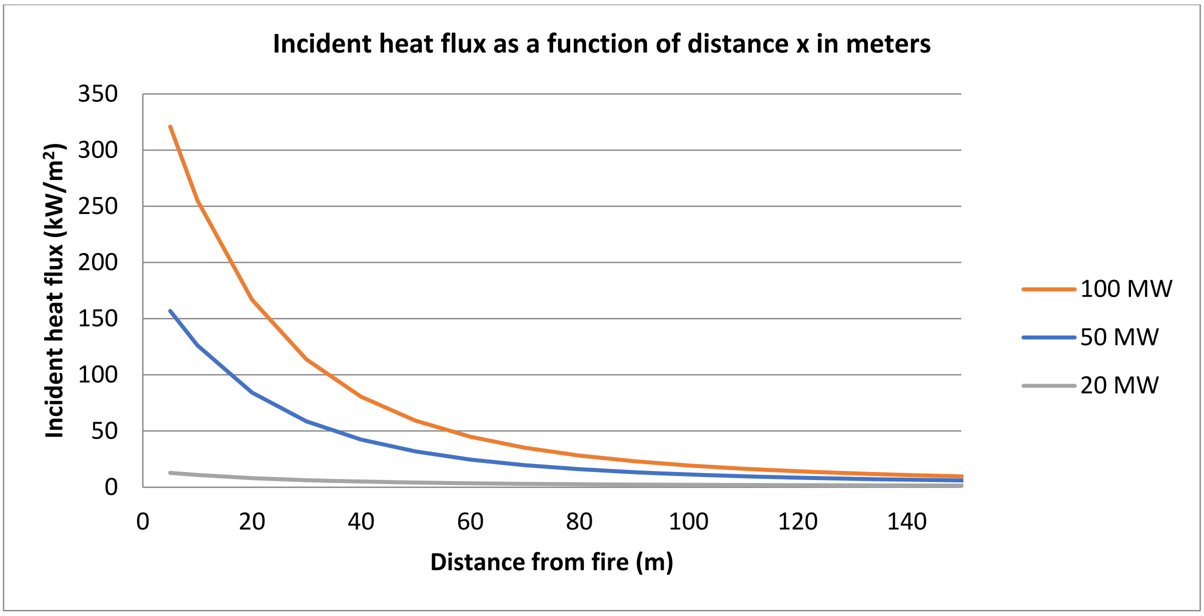

Figure 5. The incident heat flux as a function of the distance x from the fire for a 20 MW, 50 MW and 100 MW fire, respectively.

The maximum incident heat flux towards an evacuation shelter is if the fire is located just beside an evacuation shelter (x=0 m). This would mean that the maximum possible incident heat flux is about 400 kW/m^2. This is the case when 100 MW fire is used as design fire. For 50 MW design fire this will be 195 kW/m^2 and only 15 kW/m^2 for the 20 MW fire. The reason is that the incident heat flux is a function of the gas temperature up to the fourth power times Stefan-Boltzmann constant (eq. (3), see Appendix A). The gas temperatures for the 100 MW fire are 1365 °C, 1103 °C for the 50 MW and only 455 °C for the 20 MW design fire.

From the calculations of thermal impact on the shelter's outer wall, it is possible to calculate the resulting temperature behind the wall. In Figure 6 the resulting temperature inside an insulated steel fire door is shown, based on simple calculations and assumptions. Again, we refer to appendix A for assumptions and equations.

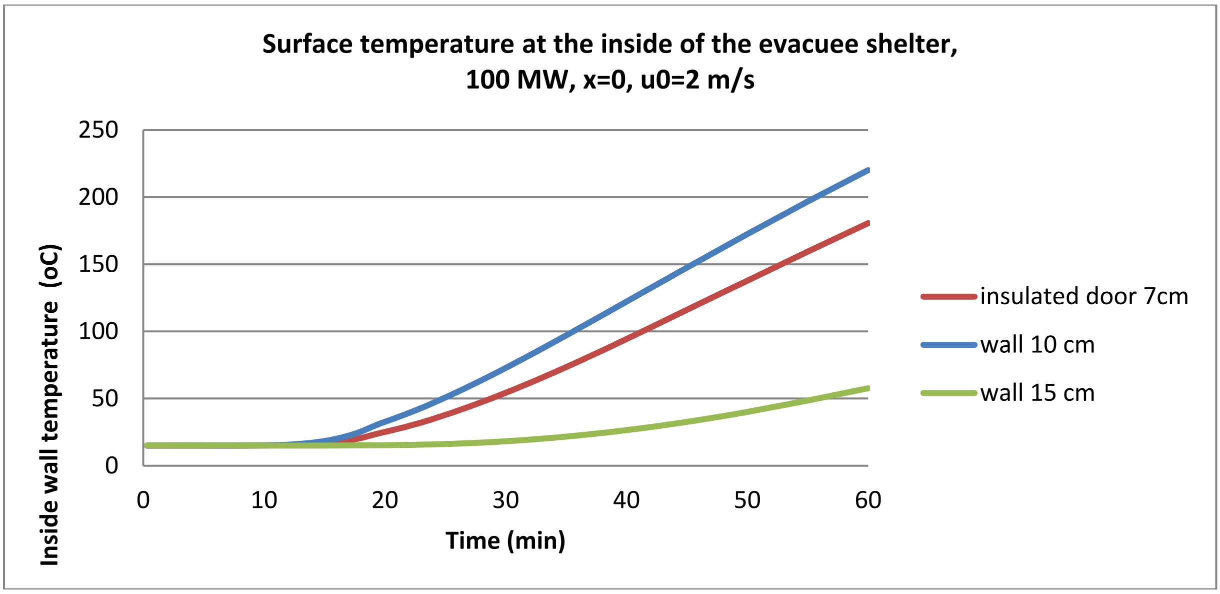

Figure 6. The inside surface temperature at a 7 cm insulated steel fire door and a 10 cm thick concrete wall exposed to a Fast design fire up to 100 MW. A surface temperature of a 15 cm thick concrete wall is also plotted.

For classification of building products that are tested and exposed to ISO time – temperature fire curves, the criterion is 180 °C, for an average of 5 points measured at the surface on the non-exposed side, and the corresponding time to obtain this average temperature defines the classification of the product. This is an example, but it shows that such an extreme fire as 100 MW fire just beside the fire wall adjacent to an evacuation shelter can withstand the heat wave up to 50 minutes for a 10 cm concrete wall and 60 minutes for an insulated steel door that is 7 cm thick. A concrete wall of 15 cm thickness or more can withstand this heat exposure with some margins. Although surface temperatures at 180 °C of the wall on the inside may appear to be high, the evacuation shelter may be situated some distance from the wall with an air lock in between.

7.4.6 Summary and future research needs

RISE finds two key uncertainties: 1) whether or not fire spread will occur, and 2) what tactic the rescue service would adapt if gas tanks were exposed to fire. Fire spread is dependent on the wind speed in the tunnel which to some extent can be controlled with fans. A sprinkler system would significantly limit the risk for fire spread and the thermal impact on wet surfaces including evacuation shelter boundaries would be negligible. However, with a sprinkler system the need for shelters in the first places is much reduced since fires will be smaller. In the future, explosion-proof gas tanks that start to leak before they burst would reduce the second uncertainty. RISE have tested such tanks that handled both local fire and extinguishment with water that cooled the TPRD. In all tests the gas leaked slowly through the material in a controlled way.

Simulation tools such as Fire Dynamics Simulator (FDS) are being widely used to study tunnel fires. They cannot accurately be used to simulate vehicle fire development inside road tunnels but could be used to estimate the risk for further fire spread to other vehicles. For this purpose, there are also hand calculation equations available.

Tunnel fires are often described in one dimension, e.g., through the maximum ceiling temperature or smoke stratification upstream or downstream the fire. However, close to the fire they are in essence three dimensional in the sense that cold air is entrained on both sides of the fire along the tunnel wall and there could be a significant temperature difference between the floor and the ceiling. For the thermal impact on shelters, this is important as the thermal impact is lowered to some extent by the cold air along the side wall as well as the colder air temperature some distance below the ceiling where, for instance, the door to the shelter is positioned. In a future study these effects could be investigated using CFD, small- or large-scale tests. A large-scale test could also serve to demonstrate that shelters handle real and severe tunnel fires.

An emergency intervention concept that first push the smoke in one direction to assist tunnel users in shelters on the fresh air side, and next reverse the flow and push the smoke in the opposite direction and assist the remaining tunnel users on the other side deserves some research. Firstly, this way of using the ventilation contributed to the large fire spread to several vehicles on both sides of the original fire in the catastrophic Mont Blanc tunnel fire (Ingason, 2003, Lacroix, 2001). Maybe not only tunnel users but also vehicles would need to be evacuated before the ventilation is reversed? Secondly, depending on the fire size and its location relative to the tunnel inclination it may not be possible to reverse the ventilation flow due to massive buoyancy forces, a plan B would then be needed.

At the time of the tragic alpine tunnel fires and the introduction of the EU directive on minimum tunnel safety in 2004 (EU-directive 2004/54/EC, 2004), FFFS was not an option for tunnel safety, however, that situation is today very different. Efficient and economically viable FFFS for rural tunnels could be researched, similar to recent developments in Sweden where sprinkler systems for large city tunnels as well as smaller rural sub-sea tunnels have been developed (Lundström, 2023). FFFS in road tunnels could reduce the installation costs for shelters if the requirements for thermal insulation are lowered. A systematic investigation of the benefits of FFFS in relation to shelters could be a future research topic.

7.5 Workshop results

On 12th of April 2023, a workshop with 28 participants was organized to present and discuss opportunities and challenges associated with SWETOs in single-tube road tunnels. The purpose of the workshop was to gather existing knowledge and determine how to approach topics, questions and possible solutions that should be further investigated. The aim was to establish an appropriate plan for studying the viability of SWETOs in long single tube tunnels. A central part of establishing this plan was a segment during the workshop focusing on discussing what knowledge is necessary to challenge existing regulations that prohibits the use of SWETOs. The workshop allowed for learning about completed and ongoing projects deemed relevant for further studying the use of SWETOs and explored the possibility of aligning and coordinating both ongoing and planned projects, and research. The workshop consisted of an initial presentation from invited speakers, and a following discussion.

Major contents of the presentations from the workshop is included elsewhere in the report. Information about pilot projects in the Flekkerøy and Frøya tunnel, as well as experiences with SWETOs in the Oslofjord tunnel, is included in section 6.1. Fire dynamics and fire scenarios, which was presented by RISE at the workshop is included in section 7.4 and Appendix A, while SINTEF's recent research on self-rescue and SWETOs are included in section 7.2. In this section we highlight the hypothesized needs for new knowledge, which was expressed through the discussion during the workshop.

Table 12. Challenges identified during workshop and possible actions. Actions are identified based on an analysis of the challenges.

Challenges identified during workshop	Possible actions based on challenges
A prohibition of a specific solution is contradicting the goal of developing performance-based regulations. The supporting documentation for the decision to prohibit SWETOs is unclear, albeit the decision is heavily impacted by the Mont Blanc tunnel fire in 1999.	It is considered necessary to analyze the background for the prohibition on SWETOs in tunnels. Was the justification of the prohibition professionally and comprehensively supported? Was this strictly banning SWETOs or were other safety measures required instead or existing measures emphasized/enhanced?
As the SWETO concept in general was considered to come with "an unacceptable risk", there does not exist European criteria by which we can evaluate the risk of SWETOs.	There are several ways of evaluating risk associated with a design. Further studies should identify relevant alternatives and provide recommendations.
To change European policy on SWETOs it must be driven by more than a Norwegian initiative. European countries' standpoints on SWETOs anno 2023 are not known, neither the countries' potential benefit of implementing SWETOs.	An actor analysis could identify relevant stakeholders and associated opinions and impact on regulation development.

Challenges identified during workshop	**Possible actions based on challenges**
It is unclear how experiences from two Norwegian SWETO pilot projects can support decision making about the future of SWETOs in a European and/or national context.	Define and measure meaningful intermediate factors which could say something about the benefits and challenges of implementing SWETOs in Norwegian road tunnels.
A change of European policy (regulation) is not the only relevant option for Norwegian tunnel safety. It is also relevant to discuss the opportunity of utilizing the leeway of the current regulation (possibility of derogations as given by Article 14) and/or implement exemptions for 2.3.4 in the regulation for only Norwegian tunnels.	Identify relevant alternative strategies and consider associated benefits and challenges.
It is unclear what is covered by § 11 of the Norwegian tunnel safety regulation and Article 14 on *Derogation for innovative techniques* in Directive 2004/54/EC. Feedback from the Ministry of transportation is that the provision can be broadly interpreted.	A legal consideration of Directive 2004/54/EC Article 14 should clarify the regulation’s intentions and constraints.
The reference level for comparing the effect of SWETOs is not clear, i.e., to compare with a design that does not include any shelters or with a design that includes emergency exits that leads to the open, and whether the reference level varies for existing and new tunnels.	Different comparisons might be useful. The goal of risk assessments should not solely be to verify compliance with regulations. Safety studies from different perspectives should produce knowledge to consider if SWETOs are appropriate in Norwegian road tunnels, and under what circumstances.
There is uncertainty associated with what factors should govern the design of SWETOs, e.g., ventilation, wayfinding systems, capacity for occupants, general surroundings, tunnel restrictions, spacing between shelters, safe occupancy time, lighting inside the SWETO, communication systems, number of barriers between tunnel space and occupancy, Wi-Fi coverage, etc. A holistic approach, considering the socio-technical system, should be adopted, acknowledging that implementation of SWETOs might necessitate changes in TCC procedures and emergency response tactics.	Safety studies of alternative evacuation system designs, which incorporate relevant knowledge to consider the importance of design factors mentioned here.
From a regulatory perspective there is a need to consider if SWETOs are appropriate for existing tunnels only, or also for new tunnels, and (in both cases) under what circumstances. Regulators should also carefully consider the balance between functional requirements and specification of detailed minimum requirements.	Regulators should develop requirements to SWETOs as part of the evacuation system in Norwegian single-tube road tunnels, starting from overall goals. The level of specification detail should be based on the risk problem and the regulator’s and regulated’s characteristics.
There is uncertainty associated with the consequences of allowing SWETOs only in Norwegian road tunnels which are not part of TEN-T. Consistency is important and different solutions on TEN-T tunnels and non-TEN-T tunnels might lead to communication difficulties and serious accidents.	Appropriate safety studies should support this decision.

Challenges identified during workshop	Possible actions based on challenges
There is different Norwegian terminology associated with SWETOs, e.g., "tilfluktsrom", "evakueringsrom" and "beskyttelsesrom".	The terms have different connotations, which should be discussed to reach an appropriate term.
If SWETOs are to become implemented in the tunnel safety regulations, it must be coordinated with peripheral regulations.	Conduct a mapping of relevant peripheral regulations and investigate possible implications, back and forth.
SWETOs might have alternative use cases, such as storages for the FRS' equipment, intermediate protection of tunnel users in need of assisted evacuation and resting places for the FRS during emergency response.	Appropriate safety studies should include alternative use cases to cover the complete set of benefits and challenges associated with SWETOs in single-tube road tunnels.
Today's practice of determining tunnel class is not considered optimal for provision of safety equipment. Tunnel class should instead be determined based on a risk assessment.	Generally, there is a need for more knowledge about influencing factors for major accident risk in road tunnels.
Implementation of SWETOs would arguably lead to a consideration of the distribution of responsibility, which currently seem to be unclear. For instance, how are responsibilities distributed between tunnel owners, tunnel users, professional drivers, and rescue personnel?	Appropriate safety studies should support evaluation of relevant decision alternatives from a safety perspective. Legal considerations should be included as part of the decision support, which also should include responsibilities associated with the alternative of not providing SWETOs.
There are currently no guidelines for the operation and maintenance of SWETOs in NPRA's Trygg Tunnel portal. SWETOs implies new equipment in Norwegian tunnels. There is a need to carefully consider the balance between standardization of solutions and the need for flexibility to accommodate local risk factors. Excessive supervision and inspection can lead to more errors and unintended malfunctioning. Combined systems to fulfil functional requirements increases complexity and the need for maintenance.	Safety studies should include a lifetime perspective associated with relevant design alternatives to include benefits and challenges associated with operation and maintenance. Studies should include experiences from existing SWETOs and/or comparable systems.
It is necessary to determine the operational consequences of maintenance-related closing and/or malfunctioning SWETOs.	Safety studies should include considerations of varying operational status of SWETOs, the associated risk and operational consequences.
The use of technology in the rooms must also consider possible future developments.	The pilots could be used for testing new technologies in real time.
Tunnel users, including professional drivers, needs education to use SWETOs.	Identify relevant actors and associated educational needs. Consider how identified actors may be targeted by educational programs and study the learning effects.
Restricting the use of the tunnel, e.g., dangerous goods, number of buses, etc, would affect what accident scenarios could occur in a tunnel and hence the design basis for SWETOs. Currently, restrictions on traffic in Norwegian road tunnels are uncommon.	Safety studies should include considerations of varying restrictions placed on the tunnel system and the associated effects on potential accident scenarios.

8 Literature study

In this chapter we extend the partners' views in the previous chapter to grasp current trends in research and how this aligns with the functional requirements (FR) developed for the systems including SWETOs, which also bases the structure of the chapter.

Considering previous research on self-rescue, and SWETOs as a part of the self-rescue strategy, it becomes clear that we cannot consider the safety effect of SWETOs isolated from the system in which they are incorporated. Restrictions on traffic affects what fire scenarios that can occur, new energy sources could affect the fire duration and accident loads, information systems affect tunnel users' behavior, a FFFS affect the heat release rate of the fire and the fire resistance of the shelter's construction elements, and so on. A SWETO is intended as a measure if untenable conditions occur in the tunnel. However, the necessary performance requirements to achieve this purpose might vary. Considerations of the SWETOs performance in each situation depend on how much we rely on other technical measures, human behavior, interactions between actors, decision making procedures, previous education, information campaigns, etc.

The knowledge which is needed to evaluate the performance of SWETOs as part of the evacuation strategy, is also necessary to evaluate the performance of the evacuation system in a road tunnel in general, i.e., without SWETOs.

Following this line of thought, the literature study has a broad scope to cover relevant elements of a safety system which incorporates SWETOs as part of the evacuation strategy. The study builds on our current knowledge, which is reported in previous sections, and aims specifically to identify recent studies that either corroborates or contradicts current knowledge.

8.1 Driving behavior in road tunnels

A considerable proportion of the population experiences anxiety, or even fear, when driving through tunnels. Anxiety increases with increased tunnel length. Two recent studies show that fear and anxiety is still an issue in road tunnels, as a major proportion (40 % in Greece and 44 % in China) of tunnel users feel anxious or uncomfortable when driving in tunnels (Kirytopoulos et al., 2017, Lee et al., 2022).

According to studies (Ma et al., 2009, Pervez et al., 2020, Yeung and Wong, 2013), rear-end collisions and collisions with fixtures are the most frequent types of accidents in road tunnels. Although it did not list accident types in such detail, a study from Norway (Amundsen and Engebretsen, 2009) found that "single off the road" and "same direction" accidents are the most frequent in Norwegian road tunnels. Compared to the whole road network, accidents involving cars traveling in the same direction occur more than twice as frequently in Norwegian road tunnels. Around 90% of these incidents may be linked to driving behaviour, making this a substantial contributing component in their causes (Dingus et al., 2016, Jindal and Mukherji, 2005). In addition to failing to keep a safe spacing between cars (Lin and Chien, 2021), over half of tunnel users do not adhere to the speed limitations in tunnels (Amundsen, 1994).

According to an analysis by Amundsen and Engebretsen (2009), a tunnel's entry zone has the greatest accident rate, which is about four times greater than the tunnel's interior. This increase may be caused by sudden changes in the environment, which raise driver stress levels (Miller and Boyle, 2015, Yang et al., 2021).

The workload of the drivers increases as they approach a tunnel, and their focus on traffic information decreases. This may occur up to 150 m prior to the tunnel opening (Verwey, 1995). Another factor that has been linked to an increase in driver stress is a reduced capacity of the brain to process important information while entering a tunnel (Miller and Boyle, 2015). Age, gender, personality, culture, and psychological characteristics can all have an impact on stress levels and the way that individuals perceive tunnels (Miller and Boyle, 2015, Wang et al., 2023a). The tunnels' design can help to lessen this level of apprehension. Shimojo et al. (1995) indicated that certain measures can help to lessen this degree of anxiety, including the level of lighting and tunnel entrance design. The perception of a tunnel can also be influenced by other elements as temperature, ventilation, noise, material choice, and colour usage (Wang et al., 2023a).

The frequency of accidents has been lower in tunnels than on the open road. However, the consequences tend to be higher if an accident occur. Chinese research shows that there is two to four times greater probability of death or injury in highway tunnels than on the open road (Lee et al., 2022, Ma et al., 2009). Norwegian research (Amundsen et al., 2001) also point at higher consequences in tunnels, but the difference is not in the same magnitude as shown by the Chinese studies. Nevertheless, higher consequences may be brought on by the tunnel's confined, narrow, and generally darker environment, which can make drivers stressed and anxious (Miller and Boyle, 2015) The environment is more hazardous during a fire due to this confinement. Schmidt-Polończyk (2023) and Kirytopoulos et al. (2023) described a tunnel accident as a low frequency event compared to the open road, but with a much greater consequence due to geometrical characteristics.

To assess underground spaces from a user standpoint, Wang et al. (2023a) constructed an assessment index, user perception of underground space (UPUS) (Wang et al., 2023a). This index is applicable to all underground areas and rates them according to eight separate criteria: space connectivity and positioning, physical environment, convenience, safety, facility, landscape, application of smart technology and environmental diversity. When examining SWETO designs, this index may also be applicable.

Passive task-related driver fatigue is an issue that is particularly prevalent in longer road tunnels. This is brought on by a lack of driver stimulation and a monotonous driving environment (Qin et al., 2021). According to studies by Qin et al. (2021), using special light belts is a viable option to relieve this fatigue. The light belts refer to bounded sections of the tunnel where the visual environment is different from the normal interior. According to the article's findings, after the first five minutes in a normal tunnel, fatigue starts to build faster. When not using light belts, this continues until the driver is "awakened" by the light from the outside at the tunnel exit. The results show the effectiveness of these light belts in reducing driver fatigue. Peña-García (2018) discusses the effect of appropriate lighting in very long underground roads to diminish the "flicker effect" (Perz et al., 2017, Dondi et al., 2012) which can cause discomfort, distraction, headache, and dizziness amongst drivers. The flicker effect is caused by periodical change in luminance, and plays a greater role in longer road tunnels, where the human visual system reaches to adapt to the surrounding environment. Continuous lines of tubes of white (cold temperature) light along the tunnel helps avoiding the flickering effect and increase the homogeneity of the tunnel environment.

To learn more about Chinese drivers' awareness, habits, and intentions when driving through road tunnels, Lee et al. (2022) conducted a survey. Although it is illegal to change lanes in Chinese tunnels, a significant number reported that other drivers "occasionally" disregard this law (43 %). Speed limits were "almost always" obeyed by other drivers in 26 % of the replies.

38% of the respondents said other drivers kept a safe distance from other cars, whereas 52% of respondents thought they kept a safe distance.

Yang et al. (2021) investigated the effects of the tunnel's acoustic environment on driving behavior and the drivers' physiological state. According to the findings, when measuring mental alertness and stress levels in drivers, the use of a siren caused the biggest reaction. Driver tiredness was created by voice prompts because they were difficult to understand, yet they had the largest impact on driving safety.

8.2 Human behavior during evacuation

Factors like technical infrastructure, tunnel equipment, safety procedures, training of staff and rescue services, as well as human factors affect the outcome of an evacuation. Key factors for a safe and effective evacuation are information about the incident and direction of evacuation (Schmidt-Polończyk, 2023). The lack of these factors has contributed to the negative outcome of several large tunnel fires in the last decades. Time is a critical factor, which is why it is important to improve and support the evacuation of tunnel users during an incident.

Orientational behavior, i.e., investigating and searching for more information, and group behavior, i.e., copy the behavior of others, is expected in unclear incidents in tunnels. Hesitation behavior is also described, e.g., that people hang around evacuation doors or waiting on the road worrying about their car or they are curious about "what happens next" (PIARC, 2008b). The questionnaire surveys of Kirytopoulos et al. (2017) and Lee et al. (2022) supports the previous knowledge, showing that tunnel users choose various actions when given alternatives. The surveys also show that 18 % of the Greek respondents and 10 % of the Chinese respondents would stop their vehicle, close the window, and wait in their vehicle when seeing a burning vehicle and dense smoke up ahead in a uni-directional tunnel. Other actions are more likely, such as attempting to evacuate on foot or trying to put out the fire. From the Norwegian tunnel fires, we also see that some tunnel users stay passive in their vehicles, while others make U-turns, direct others and attempt to put out the fire (NSIA 2013; 2015).

How social influence and hazard perception affects the evacuation process, has been researched by Schmidt-Polończyk (2023) and Kinateder et al. (2015). Casse and Caroly (2019) performed interviews with tunnel operators and showed that tunnel users often are seen as incident management "disruptors" and have inappropriate and dangerous behaviour during incidents. Schmidt-Polończyk (2023) used a post evacuation survey to measure each participants individual perception, behaviour and decision making during two full-scale evacuation experiment (in two different tunnels). The results show that the primary reason to initiate evacuation was due to the visible smoke and a fire siren and voice message. The reason for choosing a particular evacuation path was mostly chosen due to the influence of evacuation signs (90 %/68 %), secondly was the presence of the voice alarm messages (34 %/40%). When asked about the alarm information audibility, results showed that there was a larger difference between each tunnel (where 68 % rated it as very weak or passable for one tunnel, this was rated as very good or excellent by 79 % for the other tunnel). Results also show that most people chose to evacuate in larger groups. Kinateder et al. (2015) performed research on how risk perception affected evacuation behaviour, using a VR-study. Results showed that the threat level was perceived as significantly larger during a fire on an HGV carrying dangerous goods compared to the control group (which was faced with an HGV fire with no dangerous goods). Although the risk perception showed a significant difference, other behavioural parameters remained mostly similar (like exit choice, pre-movement time and movement time).

Several articles have been published on how walking speed is affected by smoke or reduced visibility. When the smoke layer is moving along the tunnel ceiling, this might block lighting and reduce visibility of the tunnel. Seike et al. (2017) and Seike et al. (2021) investigated walking speeds and assessed the relationship between the extinction coefficient and under completely dark conditions. Results showed a mean walking speed of 0,78 m/s during complete dark conditions, with a minimum walking speed og 0,43 m/s and the fastest was 1,27 m/s. It was also confirmed that age and gender had an insignificant influence on these results. It was also showed that the walking speed distribution in the darkened case was less than the case where ceiling lights were on. Ronchi et al. (2018) and Li-Yu et al. (2022) performed a similar experiment, where Ronchi et al. (2018) used a sample size of 66 and Li-Yu et al. (2022) used a sample size of 1.000. Li-Yu et al. (2022) also performed a comparison of results with previously performed experiments. Some of the other studies showed higher walking speed distributions, but these experiments included footlights or emergency signs which would make walking easier. Porzycki et al. (2018) also performed a similar experiment, but also showed that attitude (motivation) and familiarity with the situation (previous experiences) positively affected walking speeds.

The layout and design of the tunnel affect the efficiency of evacuation. Storm and Celander (2022) investigate the effect of long inclination in tunnels on the walking speed of evacuees. The study included an experiment in a 907-meter tunnel with a maximum slope of 14 %. The participants were generally young people, and not necessarily representative for the population of tunnel users. The median walking speed was around 1.4 m/s and the walking speed was on average reduced by 10 % during the movement in the tunnel. The authors find that the walking speed is correlated with the physical exertion. However, the walking speed increased during the last segment of the tunnel, maybe because of people knowing that they were close to the finish line. It was also found that participants adjusted the walking speed to a pace they could remain for a long time, and men had a slightly higher walking speed than women. Zhang and Huang (2022) report findings from Chinese research on tunnel safety, where it is found that free walking speed (not restricted by smoke) is around 1.28 m/s for "the elderly" and 1.4 m/s for "the young" people. It is not specified what is meant by "elderly" and "young", but the unrestricted walking speed is generally much faster than the fumbling walking behaviour that was seen during the Oslofjord (NSIA, 2013) and Gudvanga (NSIA, 2015) tunnel fires.

Ronchi et al. (2018) did not only look into walking speed in smoke, but also investigated how different evacuation systems can support this and hopefully increase walking speeds. The research also looked into how a combination of emergency exit design (lighting around the door), alarm signals, pre-recorded messages, way-finding arrows on the asphalt and way-finding signs can affect walking speed and exit choice. Results showed that loudspeakers had the largest contribution on increasing exit choice. This installation also showed positive results when tunnel users were walking along the opposite tunnel wall, meaning that they were able to find the exit on the opposite side of the tunnel. Lighting around exits also showed a positive effect on way-finding towards exits, which also was confirmed by both An et al. (2022) and Zhang et al. (2021b). An et al. (2022) also showed the effectiveness of a pre-recorded message to initiate evacuation, where 74 % of participants mentioned they were guided by this. A VR-study by Cosma et al. (2016) also showed that participants were drawn towards the lighting system along the wall, that it's purpose of guidance towards an exit was understood well. Flashing lights around emergency exits showed positive results for exit finding both by Cosma et al. (2016) and Ronchi et al. (2016a). But during the experiment by An et al. (2022) it was mentioned by several participants that flashing lights were interpreted as a sign of danger, which was most likely due to cultural differences (warning lights are always flashing in China).

Participants in Schmidt-Polończyk (2023) evacuation experiment in Poland reported lack of curbstone marking as an obstacle during evacuation in heavy smoke. Several participants tripped on the curb. Escape route markings were considered appropriate in situations with limited smoke, while inappropriate in situations with heavy smoke. From Norwegian tunnel fires it is known that evacuees use the tunnel wall to orient themselves and hitting signs and uneven tunnel walls are obstacles that affect the evacuation process (NSIA, 2013; 2015).

When stressful situations arise, it becomes challenging to change the normal pattern. Information about the new situation must be presented in a clear and understandable way. If the person is anxious, the focus is narrow and the ability to process information is limited, which calls for simple, brief, and obvious messages (PIARC, 2008b). Different studies show that stress is not solely a negative factor in evacuations, as also shown in the The Yerkes-Dodson law (Yerkes and Dodson, 1908). Human performance could improve by the right level of stress to allow for increased attention to the task at hand, i.e., showing knowledge-based behaviour (Rasmussen, 1987). In fact, the cognitive state *worry* may correlate positively with compliance to evacuation procedures (Rød et al., 2012) - taking direct action to avoid or reduce danger (MacGregor, 1991). On the other side, too much stress in time-critical situations could lead to difficulties in evaluating alternatives, which calls for clear instructions.

According to PIARC, a prerequisite for panic behavior is the feeling of running out of time, that the window for escape is closing. In such situations an individual could rush ahead of others, causing others to copy the behavior and panic may ensue. "What matters are people's beliefs about escape routes" (PIARC, 2008b). The irrational, or panic, behavior is not common. Experiences from real fires show that people, in rather hopeless situations, search for opportunities to improve their own situation and helping the group (Njå and Kuran, 2014). Schmidt-Polończyk (2023) argues that loss of visibility is an indicator of fear and discomfort during an evacuation situation. Participants in her experiments report higher degree of fear and discomfort after a scenario with dense smoke and low visibility than after two preceding scenarios with less dense smoke. One might think that the experience from two preceding scenarios would reduce the feeling of fear and discomfort during the third scenario, but this was not the case. Loss of visibility means a loss of reference points in the tunnel, lack of ability to see evacuation signs and generally a loss of ability to orient themselves about position and direction, which greatly affect how people think and act during evacuation.

8.3 Tunnel users' general level of knowledge about tunnel safety

Studies have shown that drivers' weakness in dealing with emergency situations in tunnels can be traced back to the limited information they receive on this unique environment (Kirytopoulos et al., 2020, Zeeri et al., 2020). This has also been recognized by PIARC as an issue of great concern (PIARC, 2016). A study by Vatsvåg and Olsen (2017) indicate that better knowledge of safety measures has a positive influence on perceived tunnel safety. Kinateder et al. (2013) is also looking at the effects of information on the performance of self-evacuation processes. Their study shows that behavioural training before being exposed to a tunnel incident, improves performance. Although the effect of the information fades with time, the respondents that underwent training still responds better than the control group one year after the training. Similar results are retrieved in the study of Knapstad (Unpublished). It is found that an information campaign about tunnel safety had strong immediate positive effects. The longitudinal study shows that the effect is decreasing, but also that learning is dependent on the relational force created by the interview situation. Vaa et al. (2004) argues that without accompanying measures, the effect of mass media information campaigns is practically zero. Combined measures are judged more efficient, although it is difficult to isolate and measure the effect of the information efforts.

A survey by Amundsen (1994) showed that when driving towards a fire, only a small percentage would follow instructions and leave their car to evacuate towards the nearest exit, but the majority would try put out the fire. A study by Zeeri et al. (2020) mentioned that a significant part of drivers are not familiar with more general safety equipment in tunnels. Some of the findings show that these drivers don’t have enough understanding on the proper use of a fire extinguisher or a phone booth, as well as their unwillingness to leave their car during a fire. Lee et al. (2022) reported that a large percentage (70 %) know about equipment like an emergency phone, but only a relatively small percentage (41 %) would actually use this to contact authorities. A large portion of tunnel users are also unaware of that a specific radio frequency can be used to warn them of an incident (Kirytopoulos et al., 2020). About 20 % of the respondents in a Chinese survey believe that they can take shelter in the tunnel’s telephone booths in case of a fire. 18 % of the Greek respondents and 10 % of the Chinese respondents declared that they would take shelter in their own vehicle in case of a fire (Lee et al., 2022, Kirytopoulos et al., 2020).

A survey by Schmidt-Polończyk et al. (2021) in Poland showed, that only a small percentage (16 %) answered questions about tunnel safety correctly for more than 50 % of the questions. But when receiving proper information, tunnel users are more prone to avoid risky behaviour (Kirytopoulos et al., 2020, Zeeri et al., 2020, Amundsen, 1994, Kirytopoulos et al., 2017). This has led Kirytopoulos et al. (2021) and Kirytopoulos et al. (2023) to develop a VR tool which can contribute to educating drivers on correct behaviour when driving through a tunnel.

Research suggests that there is limited respect for less-informative signs and signals in road tunnels. A rather large proportion of respondents (72 % in Greece and 63 % in China) declare that they would continue driving if they do not see any obvious danger although they are confronted with a red light. The ignoration of control signals in road tunnels is also shown in other research studies (Papaioannou and Georgou, 2003, Kinateder et al., 2013, Voeltzel and Dix, 2004, Ronchi et al., 2016a, Jenssen and Moscoso, 2021). Kirytopoulos et al. (2017) suggest that drivers want to continue their route since there are many reasons for them to reach their destination. Only 24 % of the Greek and 30 % of the Chinese respondents would stop and wait for further information when confronted with a red light (Kirytopoulos et al., 2017, Lee et al., 2022).

8.4 TCC operators’ ability to gain situation awareness and communicate

It has already been discussed previously how effective loudspeakers and lighting systems are at initiating evacuation and guiding tunnel users towards emergency exits. This can either be a combination of systems which only needs activation (pre-determined) or something which needs activation based on information of the actual incident. The first option would provide a solution which can be seen as the simplest for tunnel operators, as no critical thinking or situational awareness is required. The second option would provide a more flexible solution, which can be adjusted to the actual event. But this would require the tunnel operator to have more situational awareness and knowledge on how safety equipment affect an incident and the evacuation of tunnel users. The importance of tunnel operators to guide tunnel users to adopt the required behaviour has been highlighted in several studies (Casse and Caroly, 2019). One way to have a more direct communication between a tunnel operator and user, is with variable message signs in the tunnel. Its design is important so tunnel users have a clear understanding of the required behaviour. Ilkhani et al. (2023) performed a study which looked into this, how variable message signs can be designed better for operators to communicate more effectively with tunnel users evacuating.

Casse and Caroly (2019) interviewed several tunnel control room supervisors and tunnel patrollers to improve learning from experience and operator skills. The efficiency of performing accident analysis has been claimed to contribute to the learning from mistakes by high-risk industries, like nuclear energy or aviation (Amalberti, 2001). The work by Casse and Caroly (2019) show how significant a tunnel operators role is on the outcome of an incident, both at identifying the risks involved and managing the consequences. Tunnel operators often acknowledge the strong interdependence between the operator and rescue services and that they have a shared responsibility of safety management. But rescue services might not always share this view.

Since the performance of the entire tunnel system determines how an incident develops, understanding the proper management procedures during an incident is crucial. Konstantinidou et al. (2020) used this as the setting for their investigation into the cognitive overload for tunnel operators during emergency situations. This was used to develope a system to estimate the mental workload of operators based on the available systems. By improving recruitment criteria, procedures and guidelines, training, and the control room interface design, one may also raise the performance of tunnel operators (PIARC, 2008a).

8.5 Tunnel users' ability to understand and follow instructions

Both Ilkhani et al. (2023) and Ronchi et al. (2016b) investigated how variable message signs (VMS) can be designed to optimize decision making and route choice during evacuation. To improve identification of VMS, placement is vital (Borowsky et al., 2008). For their effectiveness, the design of its message and display format is important (Wang et al., 2006). Both papers presented a large research background, both on the theory behind VMS design and a summary of relevant studies on VSM design factors. Ronchi et al. (2016b) employed the framework presented by Nilsson (2014) to incorporate *theory of affordance* on the evaluation of different designs of VMS. This framework was evaluated as successful in identifying conflicts and non-optimal designs. Zhang et al. (2021b) also incorporated *theory of affordance* in the evaluation of alarms, way-finding signs and lighting, and identified both negative side effects and factors which contributed positively. Ilkhani et al. (2023) used a binary logit model to identify the most desirable VMS out of 25 possible designs, based on the input of 409 questionnaires.

Lee et al. (2022) looked at drivers' compliance with signs and signals. The results showed that a large percentage would not comply with signals showing either to stop inside the tunnel (red cross and warning symbol) or red lights showing not to enter the tunnel. Mostly this was due to the lack of more information, like signs of danger. When notified to exit their vehicle due to a fire 70 % responded they would comply, but 51 % responded that they first would gather their belongings. A small percentage replied that they would stay in their vehicle to protect it (5 %). These behaviours have all been observed during actual tunnel fires and demonstrate how difficult it is to get tunnel users to comply with instructions.

8.6 Uncertainties about the future

New energy vehicles

Li (2019) performed a study on the fire and explosion hazards of various alternative fuel vehicles used in tunnels, and divided these fuels into four categories:

1. Liquid fuels (ethanol, methanol, etc.)
2. Liquefied fuels (LPG, LNG, etc.)
3. Compressed gases (CNG, compressed hydrogen, etc.)
4. Electricity

When comparing the hazards of alternative fuels with more common fuels, these can be much higher. Fires in batteries can produce more toxic gases and even result in an explosion. Other dangers like jet flames or different types of explosions can also occur when using these fuels (including a BLEVE, deflagration and detonation). Conclusions show that, compared to traditionally used fuels:

- Liquid fuels represent an equivalent or lower fire hazard.
- Liquified fuels can represent a higher fire hazard.
- Pressurized tanks usually produce a larger fire, but have a shorter duration.
- Jet fires are highly transient, where hydrogen will produce a larger fire compared to CNG.
- During a gas tank rupture and BLEVE, the overpressure should be relatively tolerable past 100 m. A study by Willmann and Truchot (2019) mentioned a lethal distance of 50 m from the incident.
- If a gas cloud explosion occurs (for a worst-case example), this will most likely not be tolerable. These might develop from a deflagration into a detonation.

Battery vehicles

The failing of lithium-ion batteries (LIBs), which today's electrical vehicles (EVs) mostly use, is usually a thermal runaway. This process is when the rate of heat generation inside the battery (self-heating) becomes higher than the rate of heat removal, causing a rapid temperature and pressure increase inside the cells (Held et al., 2022, Raza and Li, 2023). Propagation to other cells is highly likely due to cells inside the battery being densely packed. This process is well known, in theory. But the findings from research on the produced gases and temperatures initiating a thermal runaway of various LIBs can show considerable variation. A study by Golubkov et al. (2015) found that a minimum level of charge (LOC) exists to initiate thermal runaway. For battery at 100 % SOC thermal runaway started at 140 °C, while at 0 % SOC thermal runaway did not start at 250 °C.

A review by Dorsz and Lewandowski (2022) on comparing internal combustion vehicles (ICE) vs. EVs, show that there is a comparable risk, but characterized by a rapid change of energy release. One weakness of these studies is the battery capacities used, between 16,5 kWh and 24 kWh. Today's EVs have a larger capacity (up to 100 kWh) and this capacity will probably keep rising in the future. The study also found that at the present day, no standards or regulations exist on the suggested HRR for electric car fires (while some do exist for ICE car fires) (Raza and Li, 2023, Dorsz and Lewandowski, 2022). Several studies show an insignificant difference in maximum HRR for both EV and ICE fires, where EV fires can have a maximum HRR approximately 1-2 MW higher (Sturm et al., 2022, Wang et al., 2023b). Another important difference between EV and ICE fires, is the production of significant amounts HF during EV fires (Sturm et al., 2022, Wang et al., 2023b).

A risk specific for EVs, is extinguishing a fire. Several cases have shown a reignition (up to 22 hours) , after both the car and battery have been extinguished (Dorsz and Lewandowski, 2022). The dense design of cells inside the battery obstructs fire suppression and requires a larger amount of extinguishing agent and a longer time usage for fire and rescue services. The use of thermal imaging is recommended to verify the absence of internal flames. Tests by Sturm et al. (2022) show that the use of a firefighting lance can have a good effect on extinguishing a battery fire, by penetrating the battery pack before releasing water.

Hydrogen vehicles

Because of its exceptional qualities, including its plentiful supplies, robust solution for long-term storage, high fuel value, clean and renewable nature, hydrogen is thought to have a very promising future as an energy carrier (Bie and Hao, 2017, Carboni et al., 2022). It is generally acknowledged that an unintentional hydrogen release in the open will swiftly disperse, negating any serious hydrogen hazards. When hydrogen is unintentionally released in a confined space, like a tunnel, it represents a substantial safety issue when used in tunnels (Li et al., 2021a). This raises the need to analyse these hazards before use in tunnels.

Of all the research found during the literature search on hydrogen vehicles, most were on the use of CFD to assess consequences during an incident with these types of vehicles. Several articles were found, both by Bie and Hao (2017), Machniewski and Molga (2022), Malakhov et al. (2020) and several others. Bie and Hao (2017) showed that pressurised hydrogen would rapidly spread along the tunnel ceiling, reaching several meters within seconds. As several technical installations are placed along the ceiling in a tunnel, ignition would happen quickly. This study also looked at how the longitudinal ventilation velocity would affect the distribution of the hydrogen cloud. As expected, results show that a high ventilation velocity (6 m/s during simulations) moves the hazardous zone to the downstream side of the incident. It was also determined that when ventilation velocity increased, the growth rate of the overpressure after ignition and the attenuation rate after reaching the peak both reduced. As the ignition delay time increased, the growth rates of the overpressure after ignition and attenuation after reaching the peak decreased. The study by Gu et al. (2020) showed similar results, but also pointed towards the danger of a delayed ignition. Adequate ventilation is important to avoid the danger of a delayed ignition. Li et al. (2021a) compared the results between letting hydrogen release, when the pressure release is activated, or igniting the released hydrogen (creating an intentional jet flame).

Like all pressurised flammable fuels, a jet flame can be a realistic scenario. Hydrogen jets are very prone to be ignited due to its high reactivity (Carboni et al., 2022). Results from both a numerical and experimental study by Carboni et al. (2022) showed a flame length below 7 meters (90-450 bar, 1-5 mm release) and local temperatures above 1600 °C.

Two full-scale experiments were also found, which focused on assessing the blast wave overpressures and fireball characteristics, both by Kudriakov et al. (2022) and Carboni et al. (2022). Kudriakov et al. (2022) studied the rupture of pressurised tanks, where the energy can be divided in the mechanical energy of the compressed gas and the chemical energy of the combustion. The initial rupture produces a relatively strong blast wave, which contributes to the pre-mixing of the hydrogen with oxygen before ignition. The tests using hydrogen showed a maximum overpressure above 200 mbar over 200 m from the initial explosion, which produces lethal consequences for humans. But initial pressure of the tank affects this maximum overpressure. A tank filled up to 650 bar produced a maximum overpressure above 200 mbar at a distance of 200 m, while a tank filled up to 194 bar produced a maximum overpressure above 90 mbar at a distance of 200 m (which is below 140 mbar, the threshold for the first lethal effects).

Automation
Although the use of self-driving vehicles or automation of controlling of tunnel safety systems might eliminate the "human errors" from tunnels, the risks should not be ignored. The human factor mostly affects the probability of car incidents, not the consequences. To provide a safe tunnel for all its users, these consequences still need to be mitigated. It is uncertain what type of technology self-driving vehicles will have in the future. Will they be able to communicate with each other? Will a car which starts to burn still be able to communicate with other cars? How will these cars react when a fire or other incident is detected? Will this be predetermined or based on the directions of a human (tunnel operator)? If we rely on AI-learning to both drive vehicles and control safety systems in tunnels, how can we verify that correct behaviour is learned?

There has been relatively little research on these topics. Research by Li et al. (2021b) focused on the vehicle-to-vehicle and infrastructure-to-vehicle communication to inform the driver (like provide warnings of potential dangers). These systems improve safety by reducing the drivers' response time, but still rely on the driver to react (Zhang et al., 2023). Some forms of self-driving vehicles exist today, but these functions are limited to tasks like keeping a safe distance between cars, avoiding lane departure, etc. These systems are not able to assess a situation and chose the safest reaction when faced with a complex situation (like a tunnel fire in a single tube tunnel with bi-directional traffic).

The literature search showed there exists very little research on complex topics like those mentioned in this section. Therefore, the increased use of automation and AI represents a large uncertainty looking forward.

Geopolitical changes
Geopolitical changes can also affect the types of scenarios a tunnel might be exposed to. Many Norwegian road tunnels represent critical infrastructure either for local communities or even national interests. Tunnel closures or damages can lead to large societal costs due to delays or long detours, repair costs or weakened societal services like health care (as transportation between different areas is made much more difficult). Because of this societal value, these types of structures might be exposed to fraudulent actions to affect the Norwegian society. Relevant scenarios could be the use of explosives or other actions which can lead to casualties, large damage, and closure of tunnels. The increased digitalisation also adds to higher requirements on cyber security.

As future geopolitical changes are difficult to predict, this will add to the uncertainty of what types of future accidental loads and scenarios are relevant for both the design of SWETOs and tunnels in general.

8.7 Fire resistance of individual construction elements and combined systems' effect, e.g., fixed firefighting systems' cooling effect on wall elements

Concrete has a long history of usage as a construction material and is known for exhibiting favourable fire behaviour. It is a non-combustible substance with a high specific heat capacity and relatively low thermal conductivity. As a result, a concrete building will not fuel the fire and will only heat up gradually, protecting any steel reinforcement that may be present in the concrete (Boström and Larsen, 2006). But during some of the larger fires in Europe during the early 2000's severe damage was visible. There are several design codes for concrete structures like the Eurocodes, but these are aimed at buildings with a different thermal load during a fire and duration. The RWS-fire curve reaches a high maximum temperature, but after 120 minutes it starts a cooling phase.

The worst-case scenarios of using SWETOs would require concrete to withstand a high temperature, possibly for a long period of time. Concrete's thermal and mechanical properties are well understood up to 800°C, but beyond this point they become more limited (Boström and Larsen, 2006). To calculate the thermal conduction into the concrete, and eventually the heating of the SWETO, the concrete must keep its integrity. This will not be the case if spalling occurs, and calculating the amount of spalling is difficult to estimate. When the concrete is heated, moisture inside the material will evaporate and the concrete will dry and lose its integrity. When designing a SWETO, this factor will become highly relevant. The room needs to be protected for a certain duration and it must be proven that this material can withstand this duration. Unfortunately, there was not found any research on this.

A separate Scopus search for articles about "sprinkler" and "FFFS" in tunnels resulted in 37 selected documents from 1993 to 2023. Figure 7 depicts the average number of papers across 5-year time intervals. Although the numbers are quite small, it indicates that interest in conducting research on active fire protection systems in road tunnels have increased during recent years.

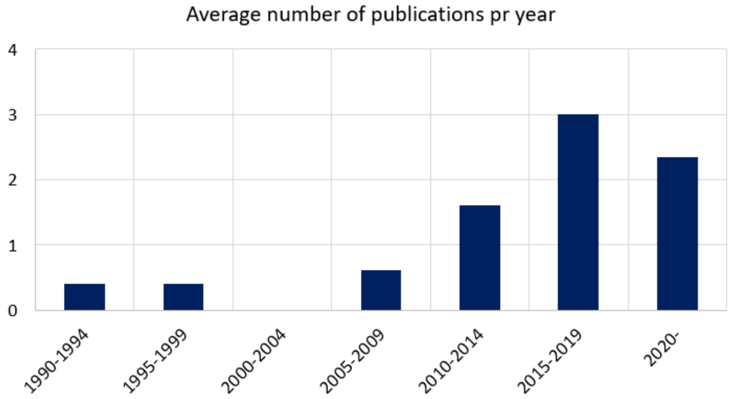

Figure 7. Time distribution of published articles about "sprinklers" and "FFFS" in tunnels.

There were several studies on the usage of fixed firefighting systems in road tunnels and how this effected the fire and its development, but none on the cooling impact of a sprinkler system on wall elements. This limits the presentation of results to this topic, but we refer to section 7.4.4 for additional reflections on this issue. It is important to mention that the performance of these systems in road tunnels often must be verified before being used in road tunnels (Cheong et al., 2014, Cheong et al., 2013). This might also limit the availability of certain details of these systems.

A deluge system, big droplet system, automated sprinkler system, or water mist system was used in the majority of the experimental studies provided in the papers. Ingason and Li (2019), Li and Ingason (2013) and Ingason et al. (2016) presented results on the use of both a deluge system and a sprinkler system. The tests by Ingason et al. (2016) showed that both the deluge system and automated sprinkler system succeeded in limiting the fire's size to no more than 30 MW. It is significant to note that during the sprinkler system test, the longitudinal ventilation velocity was reduced from 3 m/s to 2 m/s. As shown by Li and Ingason (2013), the ventilation velocity may have a negative impact of the activation of sprinkler heads as this can lead to a failure of the system. The bigger droplets did a better job of cooling the fuel surface and containing the flame spread. To prevent a critical low pressure and system failure while utilizing an automated sprinkler system, it is crucial that not too many sprinkler heads are activated. These tests also demonstrated the impact these systems have on protecting the tunnel construction.

The usage of an automatic sprinkler system with lower ventilation velocities (0,8 m/s-1,7 m/s) was the major focus of Li and Ingason (2013). The change in ventilation velocity (due to backlayering) had an influence on the number of sprinkler heads that were activated upstream of the fire, but it had little impact on the activation time. Investigations were also conducted on the effects of activation temperature and water density. Chang et al. (2017) showed the impact a deluge system may have on temperature reduction and increase in visibility (presumably because the size of the fire is reduced). Li et al. (2019) investigated the effect of adding 3 % aqueous film forming foam (AFFF) to the water supply. Although the use of foam was seen as beneficial with the presence of a liquid fire, it created a slippery environment which could cause problems to those evacuating and for rescue services. A study by Bu et al. (2022) showed similar results as the previous research presented, but reported that the activation of a water mist system would reduce visibility and decrease oxygen concentration. Zhang et al. (2021a) also used a water mist system and reported that the combustion of the fire source is strengthened to a certain extent after activation. But the water mist and vapor will absorb and attenuate the radiative and total heat flux, where its effect will increase when pressure is increased.

8.8 Fire and rescue services' (FRS) knowledge and capacity

Research on the perceived and actual competence of first responders in tunnel fire safety was conducted by Bjørnsen et al. (2023a). In Norway, the challenge around the selection of a ventilation strategy was also noted as a problem. First responders often lack sufficient situational awareness necessary to develop a plan that supports both self-rescue and allows first responders access to the incident so that search and rescue efforts may begin. The current strategy is to prioritize extinguishing the fire so that search and rescue operations can begin inside the tunnel. According to a study by Njå and Svela (2018), practices are unclear and first responders' perceived competence vary substantially.

According to Bjørnsen et al. (2023a), there is a considerable difference between full-time and part-time employees in terms of self-evaluated knowledge and competence, with full-time employees scoring higher. People in leadership positions also evaluated their knowledge and competence higher than people in subordinate positions. There was no statistical difference between being in a leadership role or not when it came to real competence. When analysing responses to open questions about a particular scenario, it became clear that most informants took a proactive approach by gaining information on the nature of the fire, the unknown goods of the vehicle, and the possibility that tunnel users might be trapped in the smoke. Most of these replies tried to clarify whether it was safe to get closer to the fire and begin search and rescue. Some informants were more concerned on the assessment of risk of the first responders, and to a lesser extent on the conditions affecting tunnel users' safety. Only a small percentage prioritized warning tunnel users through broadcasting radio messages.

8.9 Operation, maintenance, and degradation of safety measures in road tunnels

Tunnel defects and failures are frequent problems that influence driving safety. Not dealing with these issue in a timely fashion can lead to severe consequences (Ye et al., 2021). The harsh tunnel environment accelerates the deterioration of structural, civil, and functional systems. Many tunnels have complicated functional systems that must be kept in good working order to reduce fatalities and injuries in the event of an emergency like a car accident, fire, etc. These systems include lighting, ventilation, drainage, fire detection and alarms, fire suppression, communication, and traffic control (English, 2016). In USA, a manual has been developed with requirements on the maintenance of fire and life safety systems, but this manual only provides minimal requirements on maintenance (Federal Highway Administration - Office of Brigdes and Structures, 2015). There is unfortunately little research on the operation, degradation, and maintenance of safety measures. The research which was found focuses on structural degradation (deformation, structural defects, water leaks).

8.10 Summary

Summary of issues where we do seem to have strong knowledge:

- There is relevant research on driving behavior in road tunnels. However, important research within this field are older studies. It seems that we have relevant knowledge about the general behavior and the tunnel's impact on emotions and fatigue. It is more unclear how new technology in vehicles and road tunnels affect driving behavior.
- There are many studies concerned with evacuation behavior in road tunnels. Knowledge is also strengthened by thorough investigations following major fires. We know that behavior is varied and that tunnel users generally have a low level of knowledge about tunnel safety and available safety equipment.
- There are studies that investigate the effect of indirect communication between operators and tunnel users (signs, loudspeakers, lighting), which show that the systems impact behavior. However, the studies are often isolated to testing individual safety sub-systems, which makes it challenging to consider the holistic system effect when several sub-systems are combined in a specific evacuation concept.
- Research on FFFS has gained interest the recent decade and results show that the systems are effective in reducing heat release rates and protecting the tunnel's construction. However, we lack knowledge about long term operational and maintenance issues associated with FFFS in road tunnels.
- The theory behind thermal runaway of EV batteries.
- The risks of today's EV vehicles compared to ICE vehicles.
- During an incident of a tank rupture and BLEVE or a gas cloud explosion, a significant part of the tunnel will have conditions not tolerable for tunnel users.
- The theory behind thermal runaway of EV batteries.
- The risks of today's EV vehicles compared to ICE vehicles.

Summary of issues where we do not seem to have strong knowledge:

- There is limited research associated with tunnel operators' capacity and competency to effectively manage complex emergencies in road tunnels, which includes using available equipment, communicate with tunnel users and interact with other emergency responders.
- The systemic effects of FFFS combined with fire resistant constructions are not specifically investigated. The issue is relevant as there is uncertainty associated with the performance of structural elements of SWETOs during a fire with a prolonged duration, exceeding standard fire test.
- We cannot find specific peer-reviewed research on the application of SWETOs as part of the evacuation system in road tunnels. Some Norwegian studies exist, which are discussed in section 7.
- There is limited research on how the degradation of safety equipment affects the safety levels of road tunnels, as well as how to maintain them properly.
- There is limited research on the performance and limitations of FRS, when looking at

specific scenarios and geographical differences. Consequently, there is uncertainty associated with what we can expect from the FRS when we make design decisions about evacuation systems in road tunnels.
- The production of gases from EV batteries during a fire and temperatures which initiate a thermal runaway.
- How will future batteries with, most likely, larger capacity will impact safety of tunnels?
- Knowledge on how to effectively extinguish an EV fire shows some potential solutions, but more research is needed.
- FRS’ need to keep a safe distance during incidents where tank rupture or leakage is a possible scenario. More knowledge is needed on how this scenario can be identified early and how FRS’ should deal with it.
- The future of how automation will be implemented both for vehicles and tunnel safety systems is unknown today, thus representing an uncertainty on how this will affect both SWETOs and tunnel safety in the future.
- The future on how geopolitical changes will develop is unknown today. This uncertainty will affect the types of scenarios and accident loads both SWETOs and tunnels need to be designed for.

9 Analytical discussion

A thorough investigation into the performance of SWETOs as the guarantee for a proper self-rescue approach requires careful considerations about several aspects. Given that all other possibilities to evacuate in the emerging situations are abandoned, the SWETOs must meet several requirements. The rooms must be *available* for all kind of victims (tunnel-users) when they are needed. Such a statement also prerequisite that tunnel-users know that the SWETOs are present, their functions and a general acknowledgement of their service as a safe haven. The tunnel users must be able to reach the SWETOs in sufficient time to survive the emergent scenario. It means that the SWETOs must perform with sufficient *capacity* (number of tunnel-users, heat load and toxic fume ingression) over the necessary *time frames*, which means that the *survivability* of the SWETOs is of major concern.

The Norwegian population of road tunnels is large, cf. section 5. Currently, the safety standard in modern road tunnels is heavily dependent on the tunnel's traffic volume and the tunnel's length (NPRA, 2022). However, experience shows that tunnel safety is an important issue independent of traffic volume. The most serious accident until now, in terms of injured people, is the fire in the Gudvanga tunnel in 2013. The AADT in the Gudvanga tunnel in 2013 was 2000 vehicles. The AADT in in the Skatestraum tunnel when the petrol tanker fire occurred in 2015 was 300 vehicles. Steep subsea tunnels are especially exposed to fires (Njå et al., 2022). In 2009, five people lost their lives in a collision between two vehicles in the Eiksund tunnel. The tunnel had an AADT of 1800 vehicles and a maximum vertical gradient of more than 9 %. Reports in the media, indicate that high speed was contributing to the seriousness of the collision, but the collision also led to a major fire (Hedeman, 2009, Strande, 2009). The Eiksund tunnel is one of the four subsea road tunnels that stands for 50 % of the registered fire events in steep Norwegian road tunnels (Nævestad and Blom, 2023). The data retrieved from OECD/PIARC (2001), c.f. Table 4, shows that great length is not a prerequisite for major consequences in tunnel fires. In the foreseeable future, accidents and fires will continue to occur in Norwegian road tunnels. The aim is to avoid disasters. Introducing effective evacuation systems, designed with human capabilities in mind, is key.

The nature of tunnel accidents, e.g., high-energy collisions, implies that evacuation systems cannot save all. However, the self-rescue principle is fundamental for the safety of road tunnel users. The principle implies that tunnel users need to get out of the tunnel on their own and cannot expect that the FRS will be able to assist in the early phases of evacuation. Several serious fires the previous decade has led to increased reflection on the contents of the self-rescue principle, and there has been an increasing emphasis on the *facilitation for self-rescue* in road tunnels. This implies that self-rescue is not the sole responsibility of the tunnel user. Rather, it is a shared responsibility of the tunnel owner, tunnel operators, emergency responders and tunnel users, which need to be reflected and managed from the planning to the operation phase of tunnels. To comply with the self-rescue principle, we also need to comply with another important governing principle for emergency management: *the cooperation principle*. Communication is a prerequisite for effective cooperation, and the ability to control ongoing processes, such as an evacuation process, is a prerequisite for an actor to have an actual mitigating effect. Communication and control are two key ideas in systems thinking, which is the theoretical perspective from which we understand how accidents occur and safety is managed in complex socio-technical systems, such as road tunnels (Bjelland et al., 2021).

In this section we discuss the functional requirements (FR), identified in the methodology and study approach section (cf. section 2.2), that must prevail to ensure tunnel users' safety. We address important knowledge gaps and knowledge that need to be reconsidered, and finally we address ideas to increase knowledge by pilot studies as well as other designs of scientific studies. The Norwegian approach to implement SWETOs needs to encompass strong evidence-based justifications as well as practical systems to manage safety in the scattered tunnel distribution of the road infrastructure.

9.1 FR1: The tunnel’s technical systems reflect tunnel users’ behavior in accident situations

Functional requirement (FR) 1 is fundamental to all safety measures in a road tunnel, including SWETOs. This is about understanding the capabilities of tunnel users in different situations and design the support system accordingly. The support system consists of technical, organizational, and educational measures. A fundamental prerequisite for successful application of SWETOs is that tunnel users can recognize a hazardous situation when it occurs and respond to the situation in an appropriate way.

There is a need to clarify the underlying assumptions in which the tunnel’s technical systems communicate with the tunnel users. The work preceding the Directive 2004/54/EC, and the directive itself, is clear on the expectation that tunnel-specific analyses are conducted to support the design of the evacuation system. For instance, section 2.3.5 says that “emergency exits shall be provided if an analysis of relevant risks, including how far and how quickly smoke travels under local conditions, shows that the ventilation and other safety provisions are insufficient to ensure the safety of road users”. The human factor is emphasized, acknowledging that the tunnel infrastructure needs adaption to human capabilities (UNECE, 2001). The Norwegian practice of using longitudinal ventilation in bi-directional road tunnels is considered an exception, that needs justification and risk compensating measures. Major fires the previous decade show that tunnel users are trapped by the smoke, which illustrates the risk associated with this solution. NSIA is responsible for post-fire investigations, and they conclude that the self-rescue principle is not appropriately implemented (NSIA, 2013, NSIA, 2015), i.e., that some road tunnels are not designed and managed according to human capabilities, which effectively means that the intentions of the Directive 2004/54/EC are not fulfilled. We need to reconsider human travel behavior in tunnels and behavior in emergencies occurring in tunnels.

9.1.1 Driving behavior in road tunnels

The activity of driving, through sudden changes in the field of view, affect human emotions and thus our driving performance. The design of the road and its surroundings contributes to strengthen or weakening the effect of such emotions. To support drivers in adapting to the variation of roads (curves, intersections, superstructures, landmarks, etc), PIARC (2008a) recommends a clear logical design to enhance early visibility and clear understandability of critical points. If we want drivers to react or adapt behavior to new circumstances, we need to keep in mind that they are affected by their recent history. Just as we adapt our behavior to the height of the steps in a staircase, we adapt our behavior to the road. A sudden change in the staircase, or the road, causes surprises which makes us stumble. Knowledge about human behavior in normal operation of road tunnels is, first, important to prevent accidents from occurring. Secondly, it is also important to understand how infrastructures, such as road tunnels and the connecting roads, affect the drivers’ state of mind and how this governs the actions which are necessary to adapt behavior to changing situations, such as an emergency.

There have been extensive research activities related to identifying driving behavior in road tunnels. These studies show that in general people slows down speed when entering tunnels, and that average speed increases during the travel in tunnel and is at its maximum when departing the tunnel. Modern tunnels are better equipped with lighting, colors, cross-section dimensions, guardrails/-structures, automatic traffic controls, surveillance equipment, emergency niches etc., which influence driving behavior. Even though there are studies on affordance, risk perception, fear and other psychometric phenomena when driving in tunnels, these studies are not replicated to understand the performance of introduced tunnel safety measures. We have carried out a feasibility study of a drone – a rail-based system in the tunnel roof that could be used to identify hazardous situations (Njå, 2017b). Such vehicles and other surveillance systems might provide a solid base for understanding risk indicators in various tunnels. Currently, better information about the connections between driving behaviors and risk in tunnels is a major knowledge gap that does not seem to attract research activity. Differences in travel speeds, especially between HGVs and other vehicles could be an important quantity to address, technical conditions of critical vehicles with respect to released energy potential in case of fires, explosions and collisions, and general and specific competence amongst the tunnel users' awareness of hazards and risks are some of the topics that we need to elaborate.

The traffic behaviors seem to vary between specific tunnels and aggregated driving behavior between regions in Norway. How these variations influence the occurrences of incidents that imply evacuation from tunnels is also currently unknown.

The situation is regarded non-critical amongst professional environments in the NPRA other relevant actors as well as the subsequent road owners. Thus, it is difficult to raise resources to conduct sufficient studies to identify the interrelations between major incidents and driving behavior quantities (variables). The concept of real time risk analysis has been suggested by many, also by us as part of the Oslopakke 3 program studies (Njå, 2007). However there does not seem to be sufficient support to understand the connection between driving behavior and risk in tunnels better. The current possibilities with technical equipment, such as surveillance and monitoring traffic in tunnels and relevant analytical tools, such as machine learning, should be investigated for its potentials. The aim must be to clarify factors influencing incident occurrences to adapt safety measures that reduces the need for SWETOs. Furthermore, understanding psychometric issues amongst tunnel-users will ease prediction of behavior when emerging critical situations occur inside tunnels. Long and steep tunnels are anyway a threat to the tunnel users that might find themselves engulfed by smoke, which will demand use of shelters.

9.1.2 Human behavior in accident situations in road tunnels and situations associated with major uncertainties and stress

A considerable proportion of the population experiences anxiety, or even fear, when driving through tunnels (Lee et al., 2022, Kirytopoulos et al., 2017) and the anxiety increases with increased tunnel length. Information that the tunnel is in a safe state, e.g., by a green arrow above the traffic lane, would for some tunnel users reduce anxiety. Tunnels are inherently monotonous compared with the open road and measures to reduce monotony is considered positive to reduce anxiety (PIARC, 2008b). Information is also a measure that could help tunnel users overcome two important drivers of anxiety, namely perceived lack of controllability and the feeling of helplessness in coping with a stressful situation (Kim and Gustafson-Pearce, 2016, Vatsvåg and Olsen, 2017).

Kuran and Njå's study of victims in the 2011 accident in the Oslofjord tunnel revealed human behavior that was in its moment thoughtful and logical (Njå and Kuran, 2014). The interviews were recorded in hindsight and might be influenced by respondents rationalizing their own behavior. However, the cross-respondent information confirmed in general such behavior. This is related to the victims' behavior after being engulfed in smoke. Prior to that fact, the situation was characterized by huge uncertainty and lack of knowledge that postponed prompt evacuation behavior. The tunnel users were not prepared for the event. There are several studies showing that tunnel users are not aware of events requiring evacuation behavior, which is a significant task for tunnel owners and responsible authorities.

The general rule to communicate is quite simple: "in case of fire: turn around and drive out". However, real situations will add more complexity. After turning around, the driver might meet a group of people from a bus which could not turn around. It is a duty to assist others in situations where lives are threatened. Difficult dilemmas may occur in a tunnel evacuation situation, for instance if the vehicle is too small to assist a group of people. Getting into this type of situation and being faced with complex decision making represents a major deviation from the original purpose of driving through the tunnel. It should be clear that communication plays a role at several levels, from basic driver training and understanding of tunnel operation, to on-site decision support for tunnel users in challenging situations. Several studies show that signals with a low information-content are often ignored, such as a red light to close a tunnel (Lee et al., 2022, Kirytopoulos et al., 2017, Jenssen and Moscoso, 2021).

Mapping and analyzing human behavior in emergencies have various origins. Investigating accidents and real scenarios is important and interesting. However, there are few studies that incorporate real time data. For example, the NSIA rarely reflect on tunnel-users' behavior, besides being subjects for rescue. We have emphasized that the self-rescue principle implies a shared responsibility between the actors in the tunnel system. This also implies that tunnel users have responsibilities, for themselves and others. It is necessary to initiate a discussion about what we should expect from tunnel users in different situations. This discussion is also connected to operationalizing the principle of universal design for road tunnels. The potential in the pilot-projects (Oslofjord, Flekkerøy and Frøya tunnels) should be exploited to test how we can prepare tunnel users for emergencies.

9.2 FR2: The tunnel users' evacuation knowledge in conjunction with the tunnels' safety measures

Evacuation through smoke-filled areas is inherently dangerous and should be avoided. In the construction industry, schools, warehouses, concert arenas etc. the systems are designed with an aim of preventing people from evacuating through dangerous smoke. The functional requirement is that *the time available for the occupants to evacuate a building should, with a sufficient safety margin, exceed the time required to evacuate*.

9.2.1 Tunnel users' general level of knowledge about tunnel safety

There were no fatalities in the fires in Oslofjord 2011 or Gudvanga 2013, but the investigations and related research shows that the victims experienced traumatic situations, which sustains for years afterwards. Do we really know the cost associated with the injuries inflicted on the victims? On the other side, the toxicity of the smoke and the tolerance of the victims are both uncertain variables. Minor changes in circumstances might have led to fatalities, also in the Norwegian tunnel fires. Given the current situation in Norwegian road tunnels, we know that tunnel users might be exposed to dangerous smoke. We know that the evacuees will seek information and their survival instinct will drive a search for improving their own situation. If it comes to a situation where tunnel users are exposed to potentially lethal substances, such as smoke, the best advice is to minimize exposure. Today, the tunnel operators and emergency responders end up in challenging situations, where little information about the situation and no appropriate means of escape is available.

Emergency exits leading to the open is, of course, an obvious solution to consider. However, considering the Norwegian road tunnel portfolio, both cost and constructability issues arises. SWETOs are an alternative that challenges these issues. We need specific research about the non-fatal consequences of tunnel fires to better understand the individual and societal effects. Such research efforts are important to understand the potential injury-preventing benefits of SWETOs in Norwegian single-tube road tunnels. As the fundamental argument for implementing SWETOs is the cost and challenges associated with constructability of alternative solutions, we need to fully understand the cost and constructability challenges associated with the alternatives. Some ideas are discussed in Appendix B.

Knapstad (Unpublished) research shows that tunnel users' knowledge of hazardous situations that might imply immediate evacuation behavior, or their competence to evacuate, is varied. For non-stimulated tunnel-users the situation is challenging. It is possible to stimulate learning and improve evacuation behavior, but the sustained learning must be ensured by creating arenas for reflection in which the tunnel-users are exposed to critical thinking of own evacuation behavior. The pilot projects, cf. section 6.2 and 6.3, should be used as test designs to obtain an improved evacuation behavior, not only to be aware of rescue shelters, but seeing the holistic evacuation system in its proper context.

9.2.2 TCC operators' ability to gain situation awareness and communicate relevant information to tunnel users

Based on models of evacuation behavior and experiences from real events, we see that evacuation behavior (moving towards an exit) is preceded by other activities. To reach a conclusion that evacuation is the right action, the tunnel user would go through phases of detection (or realization) of the abnormal event, recognition of risk and decision making (Frantzich et al., 2016b). Tunnel operators would go through a similar process, in which the time for transition from one phase to the next would depend on the measures available for gaining situation awareness.

As we know, many existing Norwegian road tunnels are sparsely equipped with measures to detect fires and gain independent situational awareness. Tunnel operators are thus in a limited position to provide decision support to tunnel users as the situation unfolds. Several serious fires in Norway since 2011 illustrates very clearly that: 1) better communication had a potential to influence the events positively, 2) tunnel users did not receive appropriate decision support, and 3) tunnel operators (and other emergency responders) lack information to provide appropriate decision support to tunnel users. In other words, the links between the elements in the system that should provide safe evacuation are weak or non-existent. In practice, the exposed tunnel users are effectively left to themselves for decision making in a highly stressful and complex situation. Uncertainty may arise from feeling obligated to fight the fire, assist people trapped in a vehicle, notify emergency responders (use emergency phones or call 110 on their mobile phones), worrying about relatives or friends in another vehicle, lack of knowledge about available tunnel equipment and egress options, etc.

From the Oslofjord 2011 fire, we saw that tunnel operators advised tunnel users to take shelter behind the tunnel lining. The ability to provide such advise prerequisite detailed knowledge about the tunnel infrastructure. Considering the tunnel portfolio in Norway, compared with the number of tunnel operators, it seems unrealistic that the tunnel operator on duty possess knowledge in this level of detail. From previous fires we find that tunnel users report a lack of support from tunnel operators and emergency responders, and that tunnel operators and emergency responders lack key information about the unfolding situation, e.g., the location of the fire, the number of vehicles in the tunnel, the location of vehicles relative to the fire, etc. Investigation reports also identifies that the operational status of safety equipment is unknown to tunnel operators, and there are many "false" alarms from equipment in the tunnels. We also need to keep in mind that tunnel operators, after tunnel users have been caught in smoke, have limited ability to impact the evacuation process, as there are practically no means for escape available. Consequently, the tunnel operators' potential to positively influence the evacuation process lies in the initial phase. However, this is also the phase when the operators work to gain an overview of the situation.

Video surveillance and automatic incident detection (AID) are becoming increasingly common in Norwegian road tunnels. These systems provide early detection and the ability to get an overview of the situation independent of the input from tunnel users. However, counting vehicles and positioning is still a manual process. New technology intended to precisely position and track vehicles in the tunnel is promising, virtual twins could be developed to bridge the geographical gap between the tunnel and the operators, and machine learning techniques have the potential improve sensor data analysis and provide decision support for the tunnel operators (Khademi et al., 2023, Boletsis and Nilsson, 2021). Our understanding is that such technologies represent a missing communication link between important resources in the initial phase. Empowering the tunnel operators with better decision support systems, means empowering the tunnel users and the FRS' as well. This presumes a context-dependent response to events.

The current situation is, however, characterized by a strong belief in procedures and strict management focus, in which the firefighting services become in charge of the situation. The debate of victims' safety versus the need to fight the fire have not benefitted the tunnel users being in danger of smoke intoxication. There are debates about this, but anyway it is a discussion that must encompass use of SWETOs, and tunnel scenarios that are situation specific to the various tunnels. In this discussion, there is a need for all actors to acknowledge and understand the cooperation principle. The TCC-personnel easiest way to respond is predefined procedures, the FRS' prioritize the firefighting role, whilst the tunnel users have no voice in this discussion. One issue from the TCC is that the regional centers are understaffed, and they have no resolution to how they might adapt to a more flexible emergency response regime. There is an urgent need to agree upon the cooperation principle's practical solutions. Evacuation systems that include SWETOs will add to the tunnel system's complexity and require more from the tunnel operators and FRS. We need to discuss the expectations to the tunnel operators' performance in the new setting and design appropriate decision support systems that enable the operators to meet the expectations.

9.2.3 Tunnel users' ability to understand and follow instructions during an evolving accident situation

It is interesting to notice NSIA's assessment of the evacuation from the Oslofjord tunnel fire in 2017, where two HGV drivers took refuge in a SWETO and survived. NSIA state that "In this incident, the road users evacuated into a shelter where it was not possible to evacuate further into the open air. As NSIA assesses the sequence of events, it was not possible for these two road users to evacuate out of the tunnel via the tunnel on its own due to the predefined direction of the fire ventilation. In this respect, NSIA believes that the principle of self-rescue was not observed during this fire" (translated from Norwegian) (NSIA, 2018). The major issue here is the lack of interaction between SWETOs and the smoke management strategy. Due to the ventilation strategy, the SWETO was not a last resort measure, but the only resort for the tunnel users. However, NSIA acknowledges the positive contribution of the SWETO as they consider that "the shelter protected road users from exposure to both smoke and heat. Consequently, the shelter prevented road users from serious and potentially life-threatening smoke injuries" (NSIA, 2018). The event was critical, but the HGV-drivers were the only tunnel users in immediate danger who needed to evacuate.

During the second Gudvanga tunnel fire in 2015, some tunnel users were, based on experiences from the 2013 fire, told to stay in their vehicle. Considering the consequences of staying in the vehicle in other fires, notably the Mont Blanc tunnel fire, one should have a clear view of the situation in the tunnel, the potential for fire spread, and control over emergency response capabilities before issuing such a recommendation. However, it is interesting to notice that both HGV companies and operational emergency responders consider the vehicles as ad-hoc shelters in the emerging situation, which is a clear message that well designed shelters are needed. Similarly, the cavities behind the tunnel walls in the Oslofjord tunnel were considered as ad-hoc shelters in the 2011 fire. Tunnel users were recommended by TCC operators to enter this space. This illustrates the emerging problem-solving during an emergency response, where both creativity and local knowledge is important.

Road tunnel safety has predominately been a matter of providing a safe infrastructure and a set of safety equipment. Accidents and losses in different industries have often been attributed to "human error", indicating that the human element is separate from the system (Woods et al., 2010, Kinateder et al., 2013). In our context, this perspective would mean that accidents and losses occur because tunnel users are not working properly in the safe infrastructure when exposed to critical situations. The systems thinking perspective, introduced to road tunnel safety by UNECE (2001) and the Directive 2004/54/EC, should alter this position. Would it be possible to consider tunnel users as possible resources, rather than just possible victims? It could be argued that new technology is an enabler for doing so. During the 24 years since the Mont Blanc tunnel fire in 1999, there has been a great development in systems intended for; detection of events in tunnels; signaling tunnel users on-site; ease wayfinding to emergency exits; communication between TCC operators, tunnel users, and emergency responders; ease firefighting, and; decision support for TCC operators, tunnel users and emergency responders. Using a human-centered design approach, this problem could be approached by asking if the system is designed properly for its users and their prerequisites. Is the TCC data system designed so its controllers have full understanding of the complete tunnel system and how they can affect conditions inside the tunnel? Is the tunnel designed so its users understand how to react safely and as designed during an incident? By rethinking how we design and operate road tunnels with the human capabilities in mind, we would empower tunnel users to make appropriate decisions and actions in the early phase of an incident. Effective evacuation through a smoke-filled road tunnel should not be a goal for design. Such a situation should be considered as a failure of the evacuation system and as a last resort. Similarly, the use of SWETOs should not be the goal, but serve as a safer option when evacuation towards portals is prohibited.

Giving more attention to safety measures that are effective in the initial phase of the incident is in line with the primary objective of the UN's expert group (UNECE, 2001) and Directive 2004/54/EC to prevent accidents, for instance by limiting the number of tunnel users reaching the critical zone near an incident. A strengthened attention to tunnel users' needs in the initial phase effectively mean to improve the interaction between tunnel users, TCC operators and the infrastructure. Cooperation between actors to produce safety was highlighted as a key issue in the presentation of the Frøya tunnel SWETOs in the workshop 12. April (see appendix B). Communication is a prerequisite for such interactions. We claim that there is a potential to improve communication between actors in the tunnel system, but there is a need to acknowledge that situations that may occur are complex. The communication system needs to reflect this complexity. There may not be a golden rule (or message), but a need to adopt a flexible communication strategy. We often think of communication as how specific communication systems and messages affect people, but in this regard, we also include how the infrastructure communicate with tunnel users. Communication with tunnel users is essential, at least for two important reasons:

1. **Tunnel users' prior knowledge is insufficient to cope with complex tunnel accidents:** Previous experiences show that we cannot expect that road users' skill- and rule-based behavior is appropriate to select actions that match critical situations in road tunnels. Research show that tunnel users may undertake a variety of actions when confronted with a fire situation. For several reasons, being confronted with a fire in a road tunnel is a challenging, stressful, and complex situation for most road users and the communication strategy need to reflect this. We need to develop design premises, for example with respect to reliability, availability, and capacity of communication means.
2. **There is often time to improve tunnel users' performance:** Previous fires in road tunnels and fire dynamics research show that there is a time window in the initial phase of most fire events, where appropriate behavior is key to prevent losses. Hence, there is a potential to influence the behavior of the tunnel users through effective and consistent communication.

9.3 FR3: The SWETO' design to make rescue operations possible

Since the millennium the technological developments, especially related to ICT and remote communication and management systems have reformed the way society works. For tunnel safety, this opens the possibilities for arrangements to comply with the self-rescue principle. However, this is dependent on several actors, the tunnel owner, the TCC, the tunnel operators and the tunnel users. This collaboration did not work in the Mont Blanc tunnel in 1999.

9.3.1 Uncertainties related to influential past events

It is difficult to find a research paper about tunnel safety without a reference to the Mont Blanc tunnel fire on the 24th of March 1999. Information about the fire is available through several sources. The initial investigation report by Duffé and Marec (1999) is dated June 30th 1999, which is only around three months after the fire. The report has become an important reference for the aftermath. However, we also find coverage of the fire through media articles

[10], [11], research papers and Internet documentaries, such as Dark Records' *The deadly Mont Blanc Tunnel Fire 1999* [12].

Duffé & Marec's investigation includes uncertainties associated with some important issues relevant for the design of functional SWETOs. It is important to notice that these issues might be fully understood through other sources not identified during this pre-study. If so, the key is to select the relevant sources of information and exclude others. Nevertheless, the following represent examples of issues where information is ambiguous.

First, the initial investigation report state that the shelters were "fire resistant for two hours (2-hour fire rating)" (Duffé and Marec, 1999, section 4.7.3) It is not specified what time-/temperature fire curve was the reference for this classification. There are several time-temperature curves which can be used within the tunnelling environment.

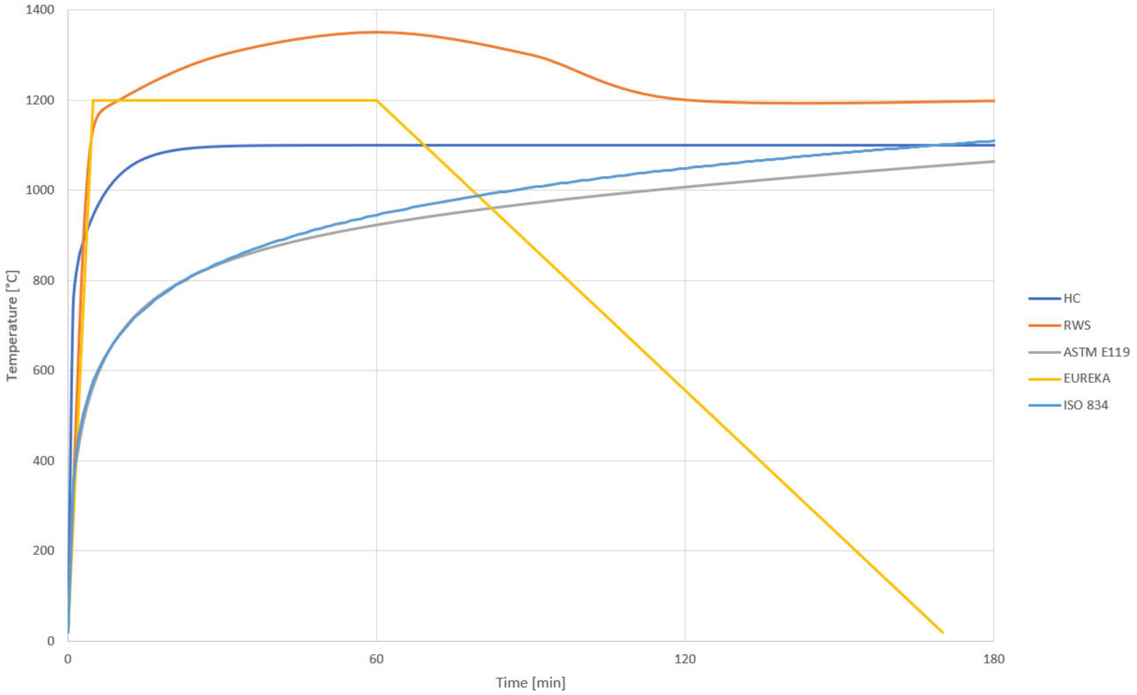

Figure 8: Different time-temperature curves, possible to use within the tunneling environment

It is natural to assume that it was the ISO 834 standard time-/temperature curve, which reaches a temperature of 945 °C after one hour and 1050 °C after two hours. In the risk analysis conducted after the Oslofjord tunnel fire in 2011 (Safetec, 2011) we find the statement that the Mont Blanc shelters were designed for 800 °C, which is also repeated in the memo from SINTEF, cf. section 7.2. In the New York Times article referenced above, it is stated that "the refuge had a fire door rated to a "four-hour" standard". There seems to be ambiguity concerning the original design premises, which we think is due to the conclusion had already been made. Documents from trials in the aftermath of the event might illuminate the facts.

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[10] https://www.nytimes.com/2019/03/21/business/mont-blanc-tunnel-fire-anniversary-rescue.html

[11] https://www.dw.com/en/the-security-features-of-the-mont-blanc-tunnel/a-18591388

[12] https://www.youtube.com/watch?v=tcLaogBvilA

Second, we have not been able to identify how the shelters in Mont Blanc were constructed. Through the Internet Documentary referenced above, we see different pictures of shelters. At some pictures it seems as if the shelters are covered by a concrete wall, while other pictures show a sheet construction. The doors seem to have windows, where the window size is variating in different pictures. It is important to understand how the shelters were protected. Two fire-resistant structures might have the same classification but could have very different performance in a real fire. For instance, the fire wall protecting the SWETOs in the Oslofjord tunnel is a 300 mm LECA wall. From the product documentation we see that all LECA walls with a thickness > 150 mm correspond to an EI 240 fire resistance, i.e., a four-hour fire rating, with reference to the standard ISO 834 curve. From this information it is reasonable to assume that a 300 mm wall would have an actual fire resistance of more than four hours. However, some constructions are more optimized to a specific fire resistance, such as drywalls in buildings. The construction will withstand the standard test-fire exposure, such as the LECA wall, but might be less robust to handle real fires. Consequently, it is important to obtain credible information about the actual construction of the shelters in Mont Blanc, and especially the construction of shelter 20, where the two people died. The investigation report makes the following assumption: "It is very likely that, even if these refuge areas had been fire-rated at 4 hours, their deaths would not have been avoided. In fact, the fire burned for more than 50 hours" (Duffé and Marec, 1999). Uncertainties from the past needs to be exchanged with solid scientific works on the current tunnel situation, and in the combination with sociotechnical systems, that are still subjected to innovations and development.

Selecting the design load, or the necessary fire resistance time, is essentially a value judgement. Resources spent on fire resistance, is resources not available to other important issues. However, if we consider the systemic effect of a robust fire-rated wall and a cooling sprinkler spray (cf. Appendix A), it might be possible to protect the structure for as long as the water flows.

Third, we have not been able to confirm the cause of death for the two people in shelter 20. The initial investigation report does not describe the cause of death of the two people. Voeltzel and Dix (2004) state that the two people in shelter 20 "died from heat after several hours in a shelter" but Informant 1 (2022) expresses uncertainty about whether it could have been intoxication because of smoke penetration. It should be a matter of investigation to identify credible information about the cause of the two people's death. Based on available information it looks like there was only a single fire-rated door between the tunnel space and the occupants in the shelters. Most fire-rated doors will have some leakage around the edges, which is why it is important to maintain over-pressure inside the protected room. An interlock space, which is part of the design in all the Norwegian tunnels' SWETO concept, is appropriate to reduce the leakage rate from the tunnel space to the protected space.

Fourth, the investigation report assumes that tunnel users in the tunnel space, trapped by the smoke, could not find emergency exits without assistance: "The victims who did get out of their vehicle and died in the tunnel did not enter a refuge area. They were surrounded by smoke and in darkness (the lighting was out from 11:01 on). They must have simply tried to flee via the tunnel. It is likely, given experience noted in other vehicular tunnel fires around the world, that they would not have reached an emergency exit without having been led there by qualified personnel" (Duffé and Marec, 1999, section 4.7.4). It seems as if the message from this statement, intended or not, is that tunnel users are unable to find emergency exits or SWETOs without assistance from professionals. This statement was therefore the major issue in a study by SINTEF on wayfinding in road tunnels at low visibility (Jenssen et al., 2018). The SINTEF-study concluded that, given appropriate wayfinding systems are installed in the tunnel, tunnel users will find emergency exits or SWETOs. The Oslofjord tunnel fire in 2011 might also serve as an example of people being trapped in the smoke, but continuously searching for ways to improve their situation, for instance by finding and occupying phone booths and crawling through hatches to the space behind the vault, only based on instructions from TCC operators (NSIA, 2013, Njå and Kuran, 2014). Generally, tunnel users are resourceful people, who can manage challenging situations, given appropriate support from the technical infrastructure, TCC operators and the emergency responders. Another way to interpret the statement above, is simply as a judgement of how effective safety corridors (exits leading to an escape route to the open) would have been if they were installed before the Mont Blanc fire. SWETOs and such emergency exits suffer the same challenges in this regard and effective wayfinding solutions are necessary. Since 1999, there have been major developments in the field of wayfinding systems, and the situation is hardly comparable any longer.

9.3.2 Fire resistance of individual construction elements and combined systems' effect

The SWETO construction elements' resistance to real accident loads is of major importance, and in particular fire resistance. We can interpret fire resistance in two perspectives: "as tested" according to a standard time/temperature curve, or "as performed" when exposed to a real fire. We have been touching upon this difference in the previous section, when discussing the SWETOs in the Mont Blanc tunnel in 1999. Two construction elements may have the same normative fire resistance, but one may perform better in a real fire, simply because the standardization test was terminated when the element satisfied a desired fire rating, say EI240. For construction elements in normal buildings, a fire rating above EI 240 is not common and the elements are not tested longer than necessary. Testing construction elements for hours, or days, would involve serious challenges for the test facilities due to heat and smoke exposure.

The accident load on construction elements in a real fire might be considerably different than in a fire resistance test. This is an especially relevant issue in tunnels, as there may be a considerable distance between a fire and the protected space. In normal buildings we can assume a uniform maximum temperature in the whole room after the occurrence of a flashover. This assumption is not reasonable in tunnel fires. Ingason et al. (2011) performed several fire tests in the Runehamar tunnel in 2003. Based on these tests, the following equation was proposed to calculate the temperature downstream of a fire, with longitudinal ventilation:

$$\frac{\Delta T_c(x)}{\Delta T_{c,max}} = 0.57\exp\left(-0.13\frac{x}{H}\right) + 0.43\exp\left(-0.021\frac{x}{H}\right)$$

The equation was verified using several large-scale fire tests, including results from the four Runehamar fire tests, the Memorial fire tests, as well as one model-scale test. The equation shows an exponential drop of maximum gas temperature x meters downstream of a fire. The equation implies a 50 % maximum ceiling temperature drop when x/H is increased by 10 (x= distance from fire, H= height of tunnel). This implies that a SWETO further away from a fire, would take on a much lower thermal load compared to the SWETO closest to the fire. This was seen during the Mont Blanc tunnel fire in 1999, where SWETO 20 seemed to have lasted for around four hours before failing (while being designed for two), while rooms further away protected its occupants up to eight hours (Duffé and Marec, 1999). If we assume that tunnel users shall use a SWETO in immediate distance to the fire, it might be challenging to design a fire-rated construction which can withstand 1 000 °C or more over several hours or days.

However, if we assume that tunnel users are led to a SWETO in some distance from the fire source, the situation is different. It is also a possibility to create interconnection between SWETOs to facilitate movement to a safer place after entering the SWETO, like how the Fréjus shelters were used by the rescue service in 2005 (BEA-TT, 2006).

When the fire-rated construction cannot be designed to withstand the thermal loads from a fire, there are several other options, such as; controlling the fire size, for instance through active systems which limit fire development; restrict what vehicles can use the tunnel in certain situations, or; rapid intervention by the rescue services.

Table 13 and Figure 9 - Figure 11 is included to illustrate that the requirements to a SWETO should depend on the *tunnel system characteristics* and the *dimensioning fire exposure*. The table and figures are meant to illustrate a way of thinking and should not be interpreted as design recommendations. The fundamental rule is that *the higher the design load, the higher the fire resistance and/or distance from the fire, is necessary*. The Flekkerøy tunnel's SWETO concept is adopting similar thinking, by locating a SWETO container within a fire protected excavated cavern. This increases the distance and number of barriers between the potential fire and the protected space inside the container. A further development of this concept could be to connect one or more SWETOs, cf. Figure 10 and Figure 11. This would provide the opportunity to move away from the fire without being exposed to the fire in the tunnel space. It could also ease the access to both evacuees and to attack the fire for the FRS because of the same reasons. Geological considerations on how to construct the interconnections between the SWETOs are discussed by Multiconsult in Appendix B.

As discussed above, there is also possibilities of providing prolonged fire resistance by taking advantage of the systemic effect of sprinklers cooling the protecting construction. However, experimental tests are needed to investigate how long the construction could last and how the sprinkler system should be designed to provide a reliable water flow for several hours.

Following a discussion of the fire-rating, is the discussion of how many hours of breathing air should be provided, and for how many people a room should be designed. A high fire resistance is of no help if there is not any air to breath in the protected space. Consequently, the discussion of design fires may not be isolated from the context or the situational scenario in which the assumed fire occurs.

There is a major knowledge base available from previous tunnel fires and tests to suggest realistic fire exposure in road tunnels under different situational scenarios. However, the choice of a dimensioning fire exposure is ultimately a value-based decision. As we see it, there is a need to establish a set of thinkable SWETO concepts and assess the concepts' performance under different accident situations. The task involves both engineering and research. Engineering involves identifying alternative concepts and consider constructability, construction costs and maintenance costs for each concept. Research is needed to identify situational and accidents scenarios in a futuristic perspective, as well as establishing a credible modeling framework to measure the concepts' performance. This study would become a decision basis to develop principal guidelines on how to investigate the robustness of SWETOs and how to make decisions about tolerable risk.

Table 13. Illustration of a way of thinking about performance criteria for shelters based on variable design loads and situational scenarios.

Design fire scenario		Shelter design			
Fire scenario	**Assumptions**	**Isolated (single) shelters**	**Clusters of two interconnected shelters (D = 250-500 m)**	**Clusters of three interconnected shelters (D = 250-500 m)**	**Shelters leading to escape path to the open**
5 MW 1 hour	Manageable scenario for external FRS in any municipality.	• Shelter's FR: REI 120-M • Air supply: 2-4 hours. • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 2 m (x m3).	• Shelter's FR: REI 60-M. • Air supply: 1-2 hour. • IFC: 1. • IFC FR: REI 60-M. • Minimum distance from tunnel area to shelter: 2 m (x m3).	• Shelter's FR: REI 60-M • Air supply: 1-2 hour. • IFC: 1. • IFC FR: REI 60-M. • Minimum distance from tunnel area to shelter: 2 m (x m3).	• Shelter's FR: REI 60-M • Minimum air supply: 1 hour • IFC: 1 • IFC FR: E 60 • Minimum distance from tunnel area to shelter: N/A.
50 MW 2 hours	Manageable scenario for most FRS' within reasonable time. Assistance from collaborating municipalities might be necessary.	• Shelter's FR: REI 240-M • Air supply: 3-6 hours • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 5 m.	• Shelter's FR: REI 240-M • Air supply: 2-4 hours • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 5 m.	• Shelter's FR: REI 240-M • Air supply: 2-4 hours • Intermediate fire compartment (IFC): 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 5 m.	• Shelter's FR: REI 60-M • Minimum air supply: 1 hour • IFC: 1. • IFC FR: E 60 • Minimum distance from tunnel area to shelter: N/A.
100 MW 5 hours	Challenging scenario for most FRS'. Could take considerable time to manage.	• Not recommended	• Shelter's FR: REI 240-M • Air supply: 3 hours • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 20 m.	• Shelter's FR: REI 240-M • Air supply: 3 hours • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 20 m.	• Shelter's FR: REI 60-M • Minimum air supply: 1 hour • IFC: 1 • IFC FR: E 60 • Minimum distance from tunnel area to shelter: N/A.
200 MW 50 hours	Challenging scenario for most FRS'. Might not be able to intervene until burnout.	• Not recommended	• Not recommended	• Shelter's FR: REI 240-M • Air supply: 24 hours • IFC: 1. • IFC FR: REI 120-M. • Minimum distance from tunnel area to shelter: 20 m.	• Shelter's FR: REI 60-M • Minimum air supply: 1 hour • IFC: 1 • IFC FR: E 60 • Minimum distance from tunnel area to shelter: N/A.

- D = Distance between shelters
- FR = Fire resistance
- IFC = Intermediate fire compartment (interlock space)

Examples of the mentioned solutions are shown below:

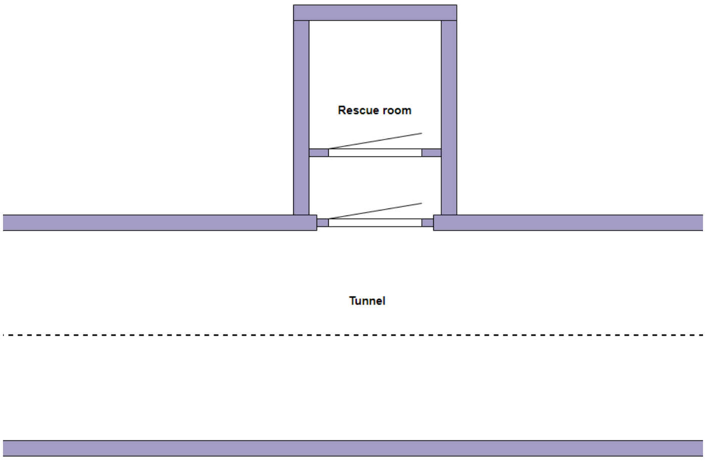

Figure 9. Connection to a single SWETO

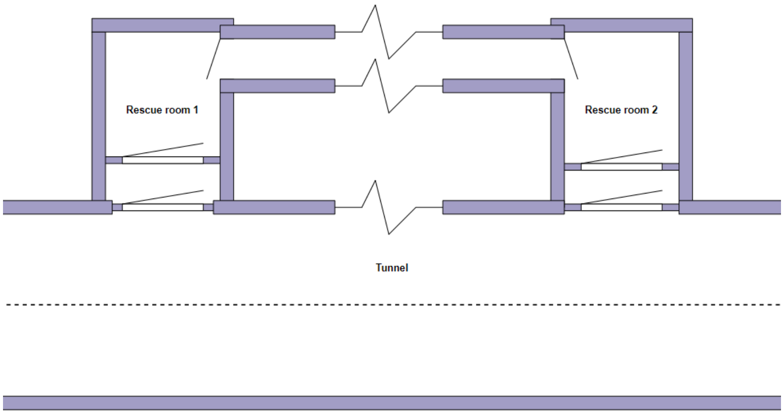

Figure 10. Cluster of two interconnected SWETOs.

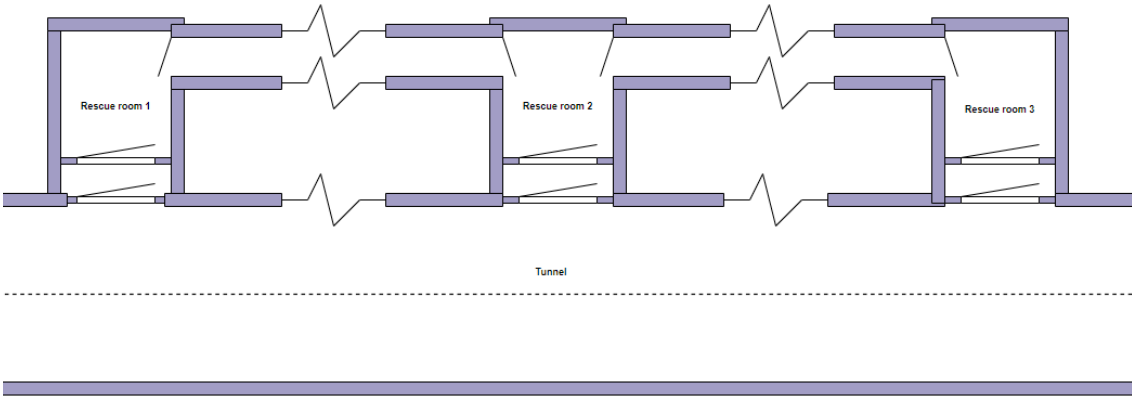

Figure 11. Cluster of three interconnected SWETOs.

9.3.3 FRS' knowledge and capacity to tackle relevant accident loads in road tunnels

There are major differences in the competence and capacity of FRS' across the country. Norwegian FRS' are expected to handle a broad scope of accidents, which require a broad set of competencies. Their organizational dimensioning and geographical location of fire stations are traditionally based on the number of inhabitants in the municipality. This implies that there might be considerable differences between FRS' performance to an otherwise similar accident.

Bjørnsen et al. (2023a) have studied first responders' perceived and actual competence in tunnel fire safety. The research by Bjørnsen et al. (2023a) shows significant variations in knowledge and competence amongst first responders within the FRS'. Systemic knowledge about the tunnels is the biggest challenge, the personnel lack knowledge of safety levels in local tunnels and how the safety systems are maintained and function. Furthermore, the research reveals that competence in the field of fire dynamics, toxicology, and human behavior in tunnel fire incidents are barely considered and not addressed in the current learning activities. Whether or not the personnel will be able to enter the accident scene is a decision that must be taken in the moment. The FRS' responses to tunnel fires are event-dependent and subject to personnel's competencies. The need for better communication and learning tools is huge and should be a topic for national authorities that can outline requirements and courses that will increase a much-needed competence.

As we have recommended for tunnel users and tunnel operators, we also need to discuss and clarify our expectations to the performance of the FRS' in tunnel fire situations. Evacuation concepts that include SWETOs increases the functionality of the tunnel, but the system also becomes more complex. Implementation of SWETOs will have to involve a reconsideration of the safety concept in the tunnel, and especially the smoke management strategy and FRS' tactics. It is foreseeable that the safety of tunnel users in SWETOs would be obtained by the interaction of their own performance (dependent on previous training and situational information), the traffic controllers' performance (dependent on training and available information systems), the technical performance of the SWETOs under accident loads, and the FRS' performance. In other words, safety is a system property, dependent on several actors' interactions in the given situation.

The FRS' are important contributors to the safety of road tunnels today. However, an implementation of SWETOs would lead to new relevant scenarios for most Norwegian rescue services. In some situations, the safety of tunnel users will become dependent on the rescue service decisions and prioritization and the time it will take to conduct appropriate intervention and/or rescue activities. The figures below illustrate a set of scenarios that could occur in a road tunnel where SWETOs are installed.

Figure 12 depicts a situation where all vehicles manage to turn and drive out of the tunnel. This is close to an ideal situation, and the FRS have flexibility to operate according to what best fits their capacity and safety. It is important that the FRS has the information that the tunnel is empty.

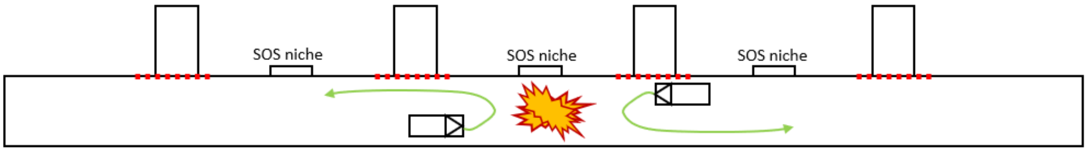

Figure 12. Scenario where all drivers are able to turn and drive out of the tunnel.

Figure 13 depicts a situation where vehicles on the right side of the fire manages to make a U-turn. On the left side, there is one vehicle and one tunnel user who is not able to escape using the vehicle. The tunnel user needs to decide what to do. There are three obvious alternatives. Priority one should be to escape through the portal if that is possible. Priority number two should be to evacuate to the SWETO farthest away from the fire, and number three is to choose the SWETO closest to the fire. Tunnel managers need to design a system these types of rules and the TCC operators need to assist in the situation. Option 3 is generally more critical than option 2, which should affect FRS' prioritization during the first response.

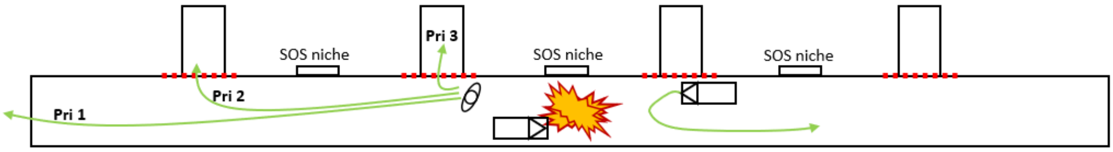

Figure 13.Scenario where evacuees are present on one side of the fire.

Figure 14 depicts a situation where vehicles on the right side of the fire manage to make a U-turn, which allows for fire ventilation from left to right when the tunnel is empty on the right side. The FRS could go into the tunnel from the left side and rescue any persons in the SWETO near the fire (pri 1) and then any persons in the SWETO far away from the fire. In theory, the tunnel users on the left side of the fire might not need a SWETO if the smoke ventilation is effective. However, the situation could occur.

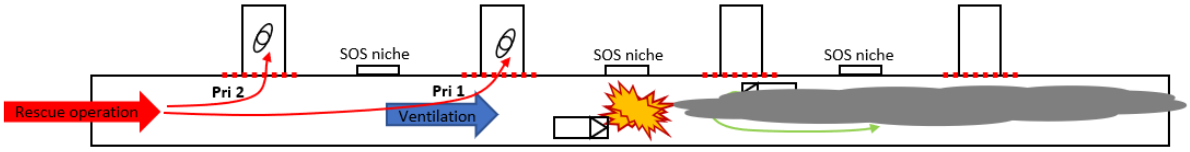

Figure 14. Scenario where evacuees are present on one side of the fire and possible smoke ventilation and first response strategy.

Figure 15 - Figure 18 depicts a situation where the ventilation flow before the fire is in the right-left direction. When the fire occurs, the ventilation could be turned off, kept at low velocity, or try to contain the smoke around the fire as much as possible, to facilitate the evacuation of tunnel users and increase situational awareness. The SWETOs on both sides of the fire are being used. In this scenario, the FRS, in cooperation with TCC operators, needs to design a context-dependent management strategy. Such a strategy would, for instance, be dependent on:

- the arrival time for rescue services,
- the distance from the fire to shelters,
- the workload (Should the FRS prioritize the less time-consuming side, versus the most populated side first? Or prioritize extinguishment of the fire?),
- the situation in SWETOs (reports of injuries, fear etc), and
- the possibility to reverse the smoke flow.

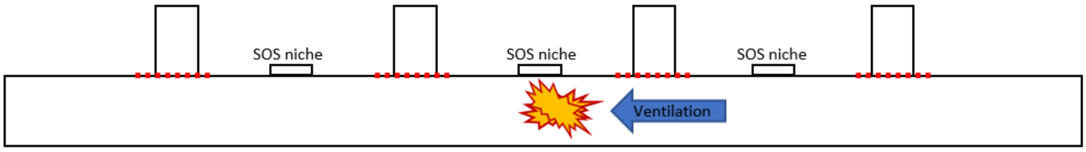

Figure 15. Initial event, ventilation towards left.

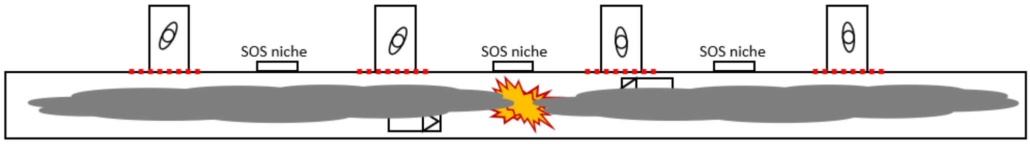

Figure 16. Ventilation terminated to allow for evacuation on both sides.

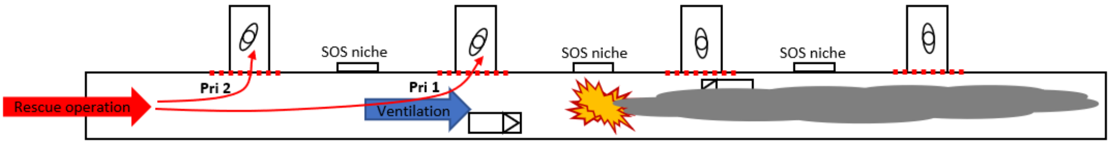

Figure 17. Rescue operation from left, ventilation from left to right. Prioritize rescue of evacuees or extinguish the fire?

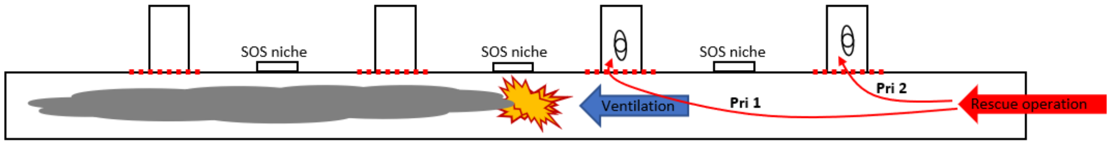

Figure 18. After clearing the left side, rescue operation from the right. Ventilation and smoke flow reversed, which is not necessarily possible. Prioritize rescue of evacuees or extinguish the fire?

Complex situations could occur when SWETOs are introduced in road tunnels. Existing safety systems, such as fire ventilation, might have constraints in functionality which provides limited flexibility for the FRS'. Such constraints must be identified and managed before the accident happens. Preparedness analyses, which include fire and smoke modelling, could be used to explore the scenarios depicted above, and discuss the feasibility of different response tactics.

New energy sources, such as gas, implies different challenges to the FRS compared to traditional vehicle fires. A considerable distance upstream and downstream of a fire exposed gas tank is considered a prohibited area, cf. section 7.4, and an offensive intervention tactic is problematic. The FRS would instead have to await that the gas vehicle burns out, cools down and regains strength before approaching the vehicle.

9.3.4 Operation, maintenance, and degradation of safety measures in road tunnels influencing performance of SWETOs

Road tunnels represent a harsh operational environment, which is a challenge to the operability of tunnel equipment. Water, salt-water in subsea tunnels, exhaust, salt, CO_2, and dust are ingredients that produce a corrosive environment. From presentations and discussions with professionals within the NPRA who is involved in inspections, we understand that it is challenging to maintain the expected technical lifetime of tunnel equipment. There are often problems with sensors, closing barriers, red closing lights, yellow blinking lights, signs, evacuation lights and safety lighting. There is often poor sound quality on DAB radio and there are challenges associated with messaging from the TCC to vehicles' radio. Some tunnels have poor technical solutions, where dust and water are allowed to penetrate to electrical components. Inspections also reveal that errors might be known for years but are not fixed. It is a general message from TCC that contractors do not report back when errors are fixed and that errors messages remain in the TCC's system for a long time. Some tunnels have tens of thousands error messages each year, many associated with AID systems. All inspected tunnels had deficiencies related to emergency drills, which is also noted by the Office of the Auditor General of Norway (OAGN, 2016). Updated risk analyses and emergency preparedness plans are missing, and technical documentation is incomplete, e.g., ventilation calculations is often missing. In practice, there are several tunnels that cannot supply the expected ventilation capacity due to maintenance and downtime on ventilators. Safety equipment, doors and sidewalks are not designed in accordance with the principle of universal design. There are often errors with emergency telephones (Wang, 2023). This latter issue is also noted by the Road Supervisory Authority after an inspection of three road tunnels in the eastern region of Norway in 2018. In two of the tunnels the random test of an emergency telephone showed that the TCC could not identify what tunnel the call came from. In one tunnel, the removal of a fire extinguisher indicated that the extinguisher was lifted from a cabinet in another tunnel (RSA, 2018a, RSA, 2018b, RSA, 2018c). During the fire in the Oslofjord tunnel in May 2017, there were several errors which are reported by NSIA as part of the fire investigation (NSIA, 2018): "Turn and exit" sign, activation of fire ventilation in the signal plan "Brannstengt", and radio messaging did not work. Four ventilators were out of order (two of which were unknown), the phone number to shelter P was registered wrong in the TCC's plans, the TCC received false alarms from seven SWETOs and two interlocks, door handles to SWETOs became very hot and led to burns, and the emergency communication system had poor functionality during the fire.

The examples above have a wide scope, from errors of technical equipment to lack of updated preparedness plans. The common feature is that they are all associated to the safety management of Norwegian road tunnels. Challenges related to proactive safety management have been noted by (NSIA, 2013, NSIA, 2015, NSIA, 2018) and the Office of the Auditor General of Norway (OAGN, 2016). In our opinion, there is a reactive safety management practice for road tunnels. There is a strong focus on compliance with minimum requirements in regulations, rather than using risk assessments or other safety studies to generate knowledge about the system's performance for management purposes. Errors remains in the system for years and there seems to be a silent acceptance for an extreme number of false alarms. In our view, this is problematic for the trustworthiness of the safety systems. Trustworthiness is essential if SWETOs are to become part of the toolbox to maintain tunnel users' safety. TCC operators need to trust the information from the tunnel, and tunnel users need to trust the information coming from TCC operator and the performance of the SWETOs. SWETOs will introduce several new technical systems in the road tunnels, and they all need to function on demand to maintain the tunnel systems' performance. On this issue, it is imperative to convince stakeholders that the future will be different from the past.

We suggest that NPRA conduct a study on the operation and maintenance of SWETO concepts, which builds on the experiences from existing SWETOs and associated safety systems. A follow-up program should be developed to collect experiences from existing SWETOs in the Oslofjord, Flekkerøy and Frøya tunnels, and a tailor-made operation and maintenance plan should be developed for any road tunnel that includes SWETOs as part of the evacuation system. The mentioned activities might all be included in the format of a risk and preparedness study of alternative SWETO concepts and tunnel characteristics.

9.3.5 Regulations, analytical framework, and systems thinking

In this section we discuss the nature of tunnel safety regulations, namely the Directive 2004/54/EC and the TSR and TSRR. We are interested in highlighting the intentions of the regulations and hold the intentions up against the Norwegian safety engineering practice. Further, we address the need for safety analyses, or a safety management framework, that addresses the major uncertainties associated with major accidents and which includes proactive management of the road tunnel systems. Finally, we address scenarios as a way of discussing reasonable safety levels. Which scenarios do we want our SWETOs to withstand? We do not aim to conclude, but to point in what direction to conduct further studies.

9.3.5.1 Regulations for tunnel safety

The Directive 2004/54/EC and the Norwegian tunnel safety regulation were implemented as a direct result of major road tunnel accidents, cf. section 3. The Directive's article 1 states the aim of the regulations: *"the prevention of critical events that may endanger human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents."* The Norwegian TSR adopts the same scope, and the same separation between *critical events* and *accidents*.

Neither "critical events" nor "accidents" are defined any further in the regulations, but from the context and work leading up towards the regulations, it seems clear that the term *critical events* refer to the major tunnel fires, like those in Europe around the 2000s. The primary aim of the regulation is to prevent such critical events to happen again. It would not be inappropriate to classify the critical events also as accidents, but in this context, accidents refer to more frequent road accidents. This is an important backdrop for working with tunnel safety in the context of Directive 2004/54/EC and TSR/TSRR. They need to be seen as regulations that primarily aim to provide a minimum safety level in the context of *critical events*. Consequently, we cannot claim that critical events are improbable and direct all our attention to the frequent road accidents. In fact, there are several other regulations under the Road Traffic Act and the Road Act that aims to prevent road accidents. A curiosity in this respect is that the *Regulation for safety management of the road infrastructure (road safety regulation)*, which is an important regulation for the work to prevent road accidents on the general road infrastructure, is not applicable to road tunnels which falls under the TSR and the TSRR. This might contribute to confusion with respect to the scope of TSR and TSRR, as they are only secondarily concerned with road accidents.

Two possible outcomes of the situation are that: 1) road accidents are not given due attention in road tunnels that falls under TSR and TSRR, or 2) the TSR and TSRR are interpreted as equivalent to the *Road safety regulation* with regards to road accidents. The latter would mean that the critical events are not given due attention, as the Road safety regulation § 3 is founded on a cost-benefit approach, which tends to "discredit" critical events. When conducting risk analyses and other safety studies in the context of TSR and TSRR, it is important to emphasize that they are regulations for events with a major consequence potential.

9.3.5.2 Risk analyses in the tunnel safety context

From the examples of smoke management strategies and treatment of dangerous goods transport presented in section 3.3, it could be argued that Norwegian road tunnel safety practice stretches the limits of EU-directive 2004/54/EC (2004) and the Norwegian Tunnel Safety Regulations (2007). Considering the major portfolio of Norwegian road tunnels there might be good reasons for an adapted practice, which aims to implement cost-effective solutions that fulfills the intention of the regulations. However, the practice hinges on our ability to analyze the tunnel-specific risk and compare these measurements to the intentions of the regulations. The situations we are discussing in this study, i.e., self-rescue situations, are generally "low-probability, high-consequence events". This is something we need to take into consideration when developing our risk assessment methods and practice. Based on experiences from the major Norwegian tunnel fires, the following investigations and the intentions of the regulations, risk assessments should adopt a tunnel-specific and future-oriented perspective. The analyses must incorporate scenarios that challenges the self-rescue principle, which means hypothetical scenarios and scenarios that we have not yet seen in Norwegian road tunnels.

Risk analyses have been given an important role in Directive 2004/54/EC, and hence the TSR and TSRR. A risk analysis is basically the outset of any road tunnel design. In the context of this study, a study of risk is needed to determine whether emergency exits are necessary, whether longitudinal ventilation is appropriate and whether it is acceptable to allow transport of dangerous goods in the road tunnel. If the risk analysis does not suggest alternative risk compensating measures, the basis is to implement emergency exits in all tunnels, adopt a transverse ventilation system, and restrict transport of dangerous goods, cf. section 3.3.

The intention of the European Commission has been to develop a common harmonized risk analysis methodology (EU-directive 2004/54/EC, 2004, article 13). The following text is retrieved from ESA's response to the Icelandic Government regarding risk analysis supporting the design of emergency exits or alternative measures (ESA, 2021):

> *"The Authority recalls that no common methodology for risk analysis has been established under the Directive, and that it is for the EEA EFTA States to define a detailed and well-defined methodology for such analyses pursuant to Article 13(2) of the Directive. Nevertheless, the Directive sets out requirements on the content of such analyses. To this, the Authority notes that the analysis provided by Iceland takes into account elements such as design factors, traffic conditions, traffic characteristics and type, tunnel length and tunnel geometry as prescribed in Article 13 of the Directive. Moreover, the risk analysis and the ventilation study, overall takes into account the risk of how far and how quickly smoke travels under local conditions, as required by point 2.3.6. of Annex I to the Directive."*

As there is no harmonized European method for risk analysis, it is, as stated by ESA, the responsibility of the member states, including the EEA EFTA states, to develop appropriate methods. Based on the discussion in section 9.3.5.1, it follows that the risk analysis method is developed in the context of preventing major consequence accidents.

It is common to define risk as the product of probability, P, of an event, A, and the associated consequences, C, i.e., Risk = $P(A_i) \times C(A_i)$. It is also common to present risk as the sum of all probabilities and consequences of events, i.e., Risk = $\sum(P(A_i) \times C(A_i))$. In mathematical terms, the latter is the expression of the "expected value", which is the center of gravity in an uncertainty distribution. For instance, over a twenty-year period on a specific section of a road, we might find the historical data depicted in Table 14. There was a total of 36 fatalities over 20 years, which gives an annual average of 1.8 fatalities on the road section. If we decide to transfer the historical data to the future, we can say that the expected number of fatalities on the road section next year is 1.8.

Table 14. Number of fatalities in a 20-year period for a specific road section (hypothetical example).

		Number of fatalities					
	All	0	1	2	3	4	>5
Frequency, 20 years	80	50	25	4	1	0	0
Average annual frequency	4	2.5	1.25	0.2	0.05	0	0

If the single accident that caused three fatalities instead were a major accident causing 15 fatalities, the expected number of fatalities would rise from 1.8 to 2.4. Risk, when described as the expected value, is dominated by the high-frequency, low-consequence events. The effect increases as the probability of a major event goes down. Therefore, cost-benefit analyses favor measures directed at high-frequency accidents. This is generally a sensible way of using society's limited resources, i.e., to attack where the effect is biggest. However, the challenge is that this approach, when used as the sole basis for decision making, might increase vulnerability to the critical events where there is a major consequence potential.

Table 14 also illustrate another challenge for risk analyses. The historical data shows that there have not been any critical events, i.e., accidents with > 5 fatalities, on our road section. How should we transfer the historical data to a future situation? The simple answer is that there is no easy way of transferring historical data to the future. Historical data will probably be relevant to describe the future, but changes might occur that also changes the preconditions that produced the historical data. The future is uncertain, and the risk analyses need to reflect that. Directive 2004/54/EC, TSR and TSRR are especially concerned with establishing a minimum safety level in the context of critical events, which are associated with major uncertainties.

As mentioned above, risk is an important concept in Directive 2004/54/EC and the Norwegian TSR and TSRR. However, to answer to the expected purpose of the risk analyses in the context of tunnel safety, the NPRA, risk analysts, and engineers need to adopt a broad concept of risk. The concept needs to address that risk is associated with the future, and that uncertainty is a fundamental component of risk. It needs to include critical events and the specific challenges, tunnel characteristics and accident phenomena listed in Directive 2004/54/EC, which is also emphasized by the letter from ESA to the Icelandic government (ESA, 2021). Management of major accident-risk, which is the scope of Directive 2004/54/EC and the Norwegian TSR and TSRR, might need different analytical tools than management of risk associated with frequent accidents. For instance, the oil & gas industry adopts concepts such as *barrier management* (PSAN, 2017) to manage major accident-risk, *systems-theoretic analysis and processes (STAMP)* (Leveson and Thomas, 2018, Leveson, 2011) works from a worst case-perspective, and *resilience engineering* (Hollnagel et al., 2006) is an answer to manage systems and organizations under major uncertainties in a fast-developing world. Current risk management practice for road tunnels has severe challenges. Method is seldom tailored to the problems it is supposed to address and the purpose of the risk analyses are often to verify compliance with regulations, rather than generating knowledge about risk for the specific system under consideration. Finally, the uncertainty concept does not seem to be understood.

9.3.5.3 Acceptable level of safety? Accident loads and scenarios

The workshop on April 12th included a discussion about risk criteria and reference levels for safety for tunnel concepts that includes SWETOs. Official risk criteria do not exist, neither on a European or national level. During the development of Directive 2004/54/EC SWETOs in general was considered to come with unacceptable risk (UNECE, 2001).

Reference levels for safety is interesting, as Directive 2004/54/EC in Article 14 state that "in order to allow the installation and use of innovative safety equipment or the use of innovative safety procedures which provide an equivalent or higher level of protection than current technologies, as prescribed in this Directive, the Administrative Authority may grant a derogation from the requirements of the Directive on the basis of a duly documented request from the Tunnel Manager." To develop decision support in accordance with Article 14, there is a need to establish a reference level, i.e., a tunnel that comply with the prescribed solutions and thus becomes the definition of acceptable risk. From the discussion during the workshop, we see that "some think that a solution including SWETOs should be compared to a solution that does not include such shelters, whereas others argue that the prohibition should be considered in a context where emergency exists is part of the solution, hence this should be the reference level for evaluating the effect of shelters. What the reference level should be might also vary depending on the tunnel being new (under design) or existing." Risk studies that compare a new concept with traditional concepts are common in several industries, and similar discussions about reference level exist. At this point, it might be appropriate to conduct risk studies using several reference levels and consider the consequences in terms of solutions. The goal of such analyses would be to improve our knowledge about what could happen in situations where self-rescue is necessary, especially when SWETOs are part of the safety strategy.

Complementary to discussing risk criteria and appropriate reference solutions, a discussion about appropriate performance is necessary. How do we want our road tunnel systems to perform in different situations? The discussion would be about the performance of actors and infrastructures and should not exclude any specific measures to achieve such performance, e.g., SWETOs. A crucial factor is how long the room is designed to be used and what fire it is designed to be able to resist. Several of the mentioned examples in this report have a fire rating of 2-4 hours, which should be able to provide safety for most fires, cf. table Table 4 and Appendix A. Most of the tunnel fires that have occurred in Norway, had a duration within this time frame. However, extreme examples do exist. The Mont Blanc tunnel fire in 1999 and the Brattli tunnel in 2013, lasted several days. A more recent extreme example is the Skatestraum tunnel fire, which, according to calculations, reached a peak heat release rate of nearly 450 MW seven minutes after the fire broke out. After a few minutes it stabilized at around 230 MW, before it burned out approximately 40 minutes after it started. The temperature above the burning trailer with petrol is estimated to 1350 °C (NSIA, 2016a).

9.3.5.4 Technical versus «social» engineering

Identifying the important stakeholders

It seems technical feasible to design SWETOs to withstand extreme fire loads. It is also theoretically possible to impose restrictions on traffic, to avoid co-existence of potential extreme fire scenarios and extreme "user-scenarios", e.g., avoid buses of tourists while there is transport of dangerous goods or an HGV in the tunnel. However, from the work preceding the Directive 2004/54/EC and the trauma from the Mont Blanc fire, it seems clear that designing and operating SWETOs is not just a technical engineering challenge. It is also about aligning different perspectives on risk and responsibilities, which essentially is more a social engineering challenge. It is important for those wanting to challenge the existing regulations to fully understand the foundation for the current design. This pre-study has come a step further, but still there are issues that needs further investigations. For instance, it is important to identify key stakeholder countries and people who will be able to shed light on the European process towards implementation of the Directive 2004/54/EC and risk perceptions on this issue across Europe.

To initiate the process, it was decided to develop a conference paper as part of the pre-study. The paper was presented at ISTSS 2023 in Stavanger, targeting a major and international tunnel safety and security audience. The paper was entitled "Evacuation shelters in single-tube road tunnels – From a poor reputation to emerging interest". The goal was to initiate discussions about SWETOs during the conference and to investigate different perceptions of risk associated with SWETOs. An important issue that was brought to the forefront, was the question of "who is responsible for the safety of tunnel users when they are occupying a SWETO?" In section 3.2 we discuss the use of SWETOs in the Icelandic Vaðlaheiði tunnel, where, based on a risk analysis, it was decided that available SWETOs was not strictly needed, and we pose the question of who is responsible for any injuries that might occur if these rooms are not available in an accident. The activities that are initiated with regards to SWETOs are based on an acknowledgement that the self-rescue principle is not met in several Norwegian road tunnels. The Norwegian tunnel owners are responsible for correcting this, and given the Norwegian road tunnel portfolio, SWETOs are intuitively a cost-efficient solution. Further investigations should provide an overview of important stakeholders, nationally and internationally, and their associated opinion about this matter. Without doing this work, other actions (testing, simulations, engineering) may be futile, at least if the goal is to change European regulations.

Terminology

We notice that several terms are in use on what we have called "SWETOs". Examples are "waiting rooms for assistance" (Flekkerøy), shelters, evacuation rooms and rescue rooms.

In this study we have tried to apply the word SWETOs consistently. The purpose is, of course, to relate the concept to the Directive 2004/54/EC, but also to avoid a concept that includes connotations and hints about the artefact's functionality. As we are about to reconsider SWETOs for application in Norwegian road tunnels, we believe it is important to keep an open mind about what the concept should be. For instance, using terms like "waiting room" connotate that the rooms are intended for tunnel users while waiting for someone. This excludes that the rooms might be an important part of the FRS' emergency response tactics. "Evacuation room" also indicate a functionality associated with the tunnel users. Evacuation could be defined as "the process of moving people from an area due to hazard for humans' life or health" (SNL, 2023). A shelter is usually regarded as temporarily safe, or safer than the alternative, e.g., during an air strike or a hurricane. Uncertainties about whether the real loads exceed the design loads will exist, and we could admit that there are safer places to be during an airstrike or hurricane than in a shelter. However, nature of the loads and the context often excludes the optimal alternative. If we were to suggest a term which introduces functionality, we would highlight the term "protection", or "beskyttelse" in Norwegian. SWETOs, as far as we can see, are intended to protect someone (e.g., tunnel users and emergency personnel) or something (e.g., emergency response equipment and communication systems) from unacceptable exposure to loads that will cause losses. We encourage a broad discussion about the application area of SWETOs and development of associated functional requirements, bearing in mind that "customers" of these rooms need to acknowledge them.

10 Recommendations to future research and engineering issues to address the performance and significance of SWETOs in tunnel safety management

This study set out to make a clear distinction between the activities that are needed to implement safe and reliable evacuation concepts in the pilot projects, and the activities needed to support an application to change the regulations. However, we have come to believe that the two issues are closely related. If we cannot develop a strong belief that the evacuation concepts implemented in the pilot projects are safe, or (alternatively) could be safe with some specified modifications, it might not be appropriate to initiate a process to change European and national regulations. Generally, it is also important to consider whether a change of European regulations is a relevant goal. A revised national adaptation of Directive 2004/54/EC or a "tunnel by tunnel"-oriented approach could be more suitable.

Our conclusion is that SWETOs, as a concept, is a relevant measure to solve a real and precarious challenge with a lack of self-rescue options in many existing Norwegian single-tube road tunnels. Available knowledge supports a stepwise establishment of SWETOs in selected high-risk road tunnels. The stepwise establishment should ensure learning from project to project. Learning must be safeguarded throughout the tunnel safety system and the value chain for SWETOs, so that functional requirements, technical solutions, operation and maintenance, and road user-oriented measures are challenged and developed in line with the experience gained from ongoing projects. We conclude that there are technologies and methods available to develop safe solutions that include the SWETO concept, but we are currently unable to define general minimum requirements for acceptably safe solutions in the relevant tunnel contexts.

There is sufficient knowledge available in the fields of fire dynamics and structural design to specify constructions that will withstand major accident loads. Furthermore, it is possible to connect SWETOs and add protection by FFFS, to further strengthen its fire resistance. We also know how much breathing air a group of people need for a specified time, and there are design choices available to create robust solutions. Experiences from other sectors, Norwegian tunnel fires and VR studies, indicate that evacuees will accept SWETOs as a temporary place of safety. A major concern is whether tunnel users become aware that SWETOs exist in a specific tunnel. Previous events and research show that tunnel users' behavior varies, and many awaits information from TCC operators before initiating evacuation. Previous studies indicate that it is possible to guide tunnel users in the early stages of an event, to initiate evacuation, increase awareness about available SWETOs and ease wayfinding. Pilot projects are essential in testing whether our current knowledge is sufficient. Another concern is operation and maintenance. We know that it is a challenge to keep safety equipment operational in road tunnels. SWETOs as part of evacuation systems implies more equipment and more maintenance. Again, pilot projects are essential in developing trustworthy operation and maintenance plans which makes sure that the SWETOs are available when needed.

Three testcases in the Norwegian road infrastructure, the Oslofjord, the Frøya and the Flekkerøy tunnels include SWETOs as well as other innovations that are/will be implemented to gain experiences. The Oslofjord tunnel's SWETOs have been in operation for ten years. These are valuable assets to organize observations and experiences that is much needed.

It is the responsibility of the tunnel owner to develop trustworthy arguments about the pilot projects' evacuation systems. It is the responsibility of the Norwegian Public Roads Directorate to consider whether the arguments are strong enough to generalize the concepts beyond pilots, which includes initiating a process to change the regulations on a national and/or European level. An important part of the follow-up work of this report is to establish a co-operation between the Ministry of transport (responsible for the application/proposal) and the NPRD to communicate with professional agencies in the various countries, and to justify use of SWETOs.

The pilot projects cannot solely provide sufficient information, and there is a need to define topics that require research and engineering designs that will support and justify future decisions about SWETOs as efficient parts of the tunnel's safety management systems. Our findings indicate that knowledge gaps may be categorized as issues related to:

1) our understanding of the background for prohibiting SWETOs and opinions about future policies;
2) safety management of Norwegian road tunnels, and;
3) design variables and engineering processes.

The three major topics are illustrated as three interconnected nodes in Figure 19 along with a set of issues by which we need more knowledge. In the center we have illustrated the knowledge-generating research and development activities. The pilot projects, which includes R&D activities associated with the implementation of SWETOs in the Flekkerøy and Frøya tunnels, is an example of the latter. We have added the Oslofjord tunnel, as it represents a valuable data source on the operation and maintenance of SWETOs in the Norwegian road tunnel context. However, the pilot projects represent one out of many tools for knowledge generation on the major topics.

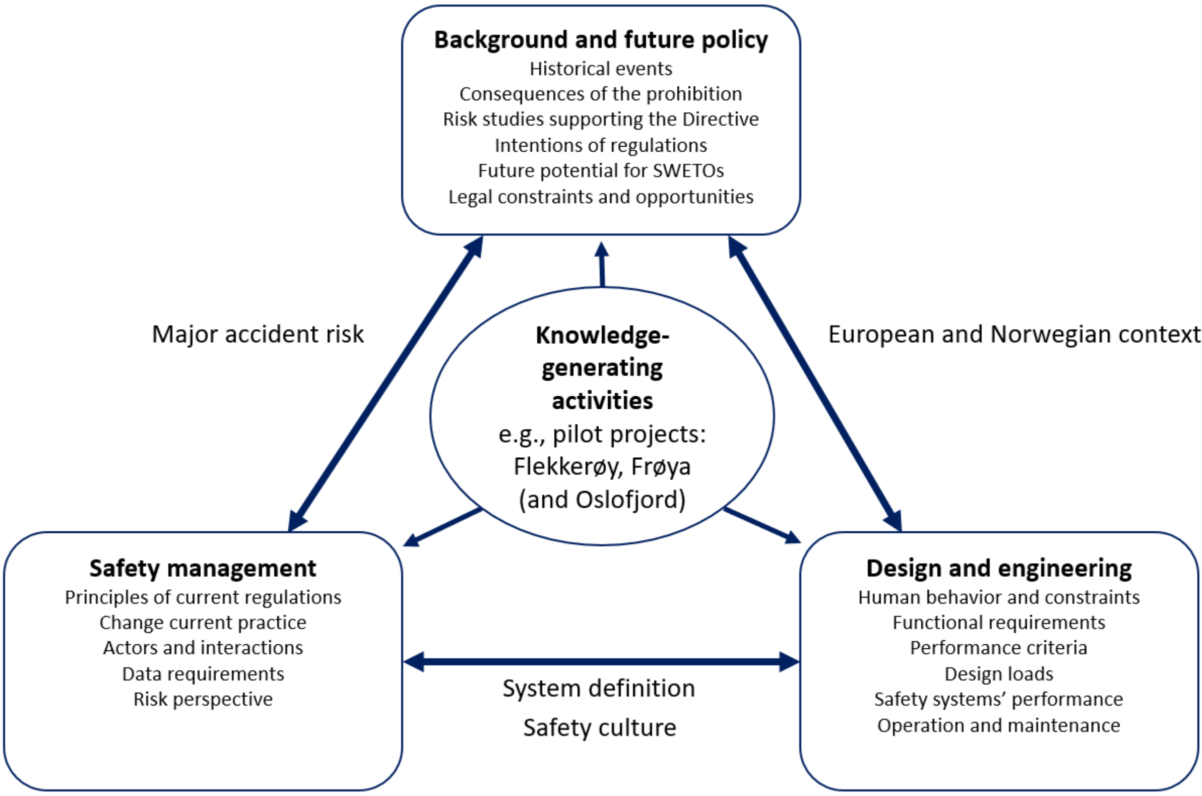

Figure 19. The structure of major topics to improve strength of knowledge to develop trustworthy evacuation concepts that includes SWETOs.

It is essential that we understand the background of current regulations to implement proper safety management systems to obtain functional design and engineering practices. On the other hand, new knowledge related to safety management and design and engineering practices, should also affect future policies. Since we are dealing with novel safety concepts, there is no clear distinction between research and development on the one side, and design and engineering on the other side.

This section presents issues and ideas, in which the current pilot projects are involved. Furthermore, we introduce ideas and issues that needs other designs than the operational pilot projects might provide. The purpose of the suggested activities in the following sections is to strengthen knowledge and improve conditions for self-rescue in tunnels.

10.1 Major topic 1: "background and future policy"

Major topic 1 is about understanding the background for the prohibition and the potential for change. The Mont Blanc tunnel fire in 1999 was essential in molding, what seems to be a rather unison opinion among European tunnel safety experts that SWETOs represent an unacceptable risk. However, there does not appear to exist any documented analysis of risks to support the prohibition. An interesting research topic is to reveal consequences to the European tunnels with regards to the prohibition. How many tunnels were upgraded and revised based on the Directive's prohibition of SWETOs, and what did it cost the tunnel owners? Issues related to self-rescue were not a major topic in Norway during the development of Directive 2004/54/EC and we did not have any tradition for using SWETOs. However, we were concerned about establishing support for the continuation of prevailing practices, such as longitudinal fire ventilation, no emergency exits in low-traffic tunnels, and greater vertical gradients, especially for subsea tunnels.

Through this pre-study, we have reached a fundamental understanding of the background. However, some of our findings needs confirmation. More importantly, the identified uncertainties associated with historical events needs clarification, as they represent situations that we do not want to re-experience.

10.1.1 Background for Directive 2004/54/EC and the prohibition of SWETOs

As mentioned above, there is a need to confirm and expand the findings of this study. It is not possible to provide a full description of such a study. However, based on our study the next steps would be:

- Clarify the reasons for implementing the adaptation specified in point 17i of Annex XIII to the EEA Agreement (EFTA, 2023). If there exist risk assessments that support this adaptation, they would be interesting to review. If such analyses do not exist, this would also be of interest along with any reasoning of why the adaptation was implemented. The intention is to obtain an equal level of safety by other measures than emergency exits, presumably within a more flexible economical and practical framework. We need to fully understand the reasoning behind the set AADT-limits (2000 per lane / 4000 per lane), vertical gradients (maximum 3 % but up to 5 % if an ALARP assessment support the choice) and smoke ventilation strategy if we are to challenge existing regulations.
- Connecting with and interviewing key personnel which were close to the processes that was undertaken in the early 2000s:
    - Key personnel within NPRA involved with the work preceding and following the Directive 2004/54/EC in international and national tunnel fora.

    - Key personnel which were involved with the meetings during the development of Directive 2004/54/EC. Collect and analyze minutes from the meetings.
    - Key personnel at CETU, France. CETU were a key stakeholder during the 1990s and 2000s. The French regulations strongly affected the Directive and representatives from CETU was involved in much of the influencing work.
    - Key personnel at the Icelandic Road Authorities to understand the reasoning behind implementing, and later demobilizing, SWETOs in the Vaðlaheiði tunnel. The correspondence between EFTA and Iceland is public, but it would be beneficial to obtain a more operational perspective on the process.

The motivation for this activity is to clarify the scientific knowledge behind the regulations, and the validity of this knowledge in the current situation. During the activities already performed we claim that SWETOs are necessary measures to obtain the self-rescue principle. The alternative might be evacuation corridors or some sort of FFFS, but this will require more studies to identify its reliability, availability and trustworthiness as a mitigation measure that postpone smoke development.

10.1.2 Understanding the Mont Blanc tunnel fire

There is a need to clarify the actual relevance of the Mont Blanc event as basis of the 2004 Directive, TSR and TSRR. This is the first important step. The fire is key to understanding the prohibition of SWETOs in road tunnels, and thus also key to understanding what we need to avoid in the future.

It has not been possible in this pre-study to go into the details of the fire and to track the available documentation. However, we have identified uncertainties associated with several key issues, e.g., the fire resistance of SWETOs, the construction of SWETOs, the cause of death of occupants in the shelter 20, etc. It is also essential to clearly understand the mechanisms that led to the extensive fire spread between vehicles and duration of the fire, and issues associated with the French/Italian bi-national cooperation to operate the Mont Blanc tunnel.

Based on its importance for prohibiting SWETOs, we recommend conducting a study specifically targeting the SWETOs of Mont Blanc before and during the fire in 1999. The study should include the following elements (not exhaustive):

- A detailed description of the design of SWETOs, including dimensions, specific materials and construction details, nominal fire resistance, penetrations, any variations among the SWETOs in the tunnel.
- A detailed description of the associated support systems, i.e., detection, notification, wayfinding, user instructions, signage, and communication, compared with available technology today.
- Investigate the existence of post-accident investigation of the SWETOs' fire resistance and structural integrity. In the case that such assessments are non-existing, calculations and/or fire simulations are recommended to assess the capacity of the SWETOs.
- An analysis of the operation procedures' impact on the evacuation process, with a special emphasis on the use of SWETOs and the effect of the ventilation strategy.
- A study of the considerations and decisions made after the fire, with special emphasis on tracing the history from the fire to the formulation of Directive 2004/54/EC appendix I section 2.3.4. Central stakeholders in the discussions and decision processes should be invited to shed light on the events.

- Investigate whether the premises for prohibiting SWETOs based on the Mont Blanc fire are still relevant, or whether they should be reconsidered. For instance, there have been major developments within the field of communication systems, signs, and wayfinding systems since 1999.

A proper understanding of the Mont Blanc accident will ensure the logics related to the Directive and the prohibition of SWETOs. It will also provide a baseline for assessing the relevance of the event for current tunnel designs. Anyway, the Mont Blanc tunnel had many distinctive features not common today, such as HGV AADT, safety management divided on two countries and heavy workloads on vehicles up to the French portal.

10.1.3 Clarify arguments for implementing SWETOs in the Norwegian and European context

In case Norway want to take the initiative to change the Directive 2004/54/EC appendix I section 2.3.4, it should be based on an investigation of the potential to improve tunnel safety in single-tube, bi-directional road tunnels on the European level. The study should investigate and describe the tunnel population on the TEN-T network where SWETOs could serve as relevant elements in the safety strategy.

If the potential beyond Norwegian borders is limited, it might be more appropriate to consider an application for a special Norwegian adaptation of the Directive 2004/54/EC. From discussions with peers during the ISTSS conference in Stavanger in April 2023, we suspect that an initiative to change the directive on one part could trigger initiatives to also change other parts. This could lead to time-consuming processes at the European level that do not necessarily lead to rapid tunnel safety improvements in Norway.

We recommend that NPRD initiate an interdisciplinary study of the change processes needed to maintain the self-rescue principle in high-risk tunnels in Norway by integration of SWETOs. The study could include the following activities (not exhaustive):

- Conduct a stakeholder analysis to get an overview of the involved actors and to understand their perspectives and opinions about the issue.
- Identify existing Norwegian road tunnels where lack of self-rescue provisions implies an unacceptable risk to the tunnel users. The identified tunnels should be prioritized regarding applicability for SWETOs based on relevant risk criteria.
- Identify and compare cost and constructability issues related to integration of SWETOs and the alternative evacuation concepts (evacuation tunnel, escape corridor, fixed firefighting systems, etc).
- Identify the consequences of smoke injuries and evacuation through smoke. The available knowledge about the costs of smoke injuries and psychological consequences of evacuation through smoke is scarce, probably underestimated, and an important argument for implementing SWETOs in Norway.
- Investigate the potential for SWETOs in other countries. The "Alpine countries" were central in the work preceding Directive EU/54/EC, and we know that Iceland attempted to build SWETOs.
- Legal considerations have not been included in this study. A legal study would be relevant to investigate and describe the constraints and opportunities included in the current regulations, and to develop strategies for further actions.

10.1.4 Justify the level of safety associated with evacuation concepts including SWETOs

Much have happened since the early 2000s in terms of technology development and our understanding of tunnel users' need for decision support in emergency situations. Consequently, we recommend that a safety study is conducted, using representative tunnels and suggested SWETO concepts in the Norwegian context. Such studies were not developed as a basis for prohibiting SWETOs in the 2000s, but they will be required as a basis to consider changing the existing opinion. See section 10.4 (pilot projects) for more details.

10.2 Major topic 2: "safety management"

Systems thinking and active safety management is a prerequisite for adequate safety for tunnel users in road tunnels in general, and especially where SWETOs are implemented. These are fundamental principles for road safety all the way back to 1997 (EC-COM, 1997), supported by UN on tunnel safety in 2001 (UNECE, 2001) and a major topic in Directive 2004/54/EC (EU-directive 2004/54/EC, 2004), and thus implied by the Norwegian Tunnel Safety Regulations. Fundamentally, it presumes that safety is a continuous control problem where control is undertaken by the actors within the system, based on real-time information about the system's performance.

Although the principles are implied by the regulations, the principles are not reflected through the current road tunnel engineering and operational practices. A transition towards more systems thinking and active safety management on a national level is a matter of culture and a major task. Nevertheless, to succeed with the pilot projects, we believe that it is essential to develop the concepts on these principles and we provide the following recommendations:

- Develop a Norwegian understanding of how to implement a system perspective and designing with the human capabilities and restrictions in mind. As part of the development, it is necessary to define the expectations and responsibilities of the system's actors in emergency situations, i.e., regular tunnel users, professional drivers, TCC operators, FRS', designers, tunnel managers, driving schools, etc.
- Set requirements for tunnel safety competence among actors who work with tunnel safety, e.g., fire protection managers, tunnel managers, fire brigade, engineering consultants, and builders.
- Implement an active safety management approach, which include:
    - "Real time management": Evacuation systems that incorporate SWETOs calls for a proactive approach from the involved actors. It is relevant to find the appropriate balance between automatic and manual surveillance and control. Promising new technologies within event detection, positioning of vehicles and humans, digital twins, simulation (VR, AR, consequences) and artificial intelligence should be considered to improve the interactions between the system's actors.
    - Data-driven analyses and processes: There is a need to improve our understanding of the traffic that runs through the tunnels and how the traffic affect risk, especially HGVs, dangerous goods transport, buses etc.
- Implement a better understanding of management of major accident risk in road tunnels. The regulations are specifically intended to deal with such risk, but current risk management practice is neglecting major accident risk.

The challenges listed in this section are general to the field of tunnel safety but needs a specific solution in the pilot projects.

10.3 Major topic 3: Design variables and engineering processes

Functional requirements are needed to understand the purpose of SWETOs. Based on functional requirements we can identify safety constraints, and communication is a major issue to enforce safety constraints. We know that the premises for appropriate communication is poor in many Norwegian road tunnels. There is lack of detection systems, positioning systems, communication systems, etc. There is also lack of knowledge associated with the effect of new safety measures. Investigations from real fires show that tunnel users search for information and tries to improve their situation. Advice from emergency responders and TCC operators are processed and used. However, we do not know whether we can reach all tunnel users, and how much faster we will obtain the desired responses. Hence, more research is needed.

Based on this study we have identified the following issues associated with design and engineering processes:

- Clarify systems thinking's and modern safety management's impact on design and engineering: Who are the important actors in the "system" and how do we facilitate an appropriate cooperation between the actors to manage safety?
- Acceptable safety should be considered based on a trustworthy argumentation that important processes and safety constraints are under control in the specific road tunnel. To understand whether there is control, we need to understand the goal of the system and whether they are obtained. We also need to have a common agreement about the loads that define the contexts in which we should have control. On the regulator's side, this implies developing:
    - Functional requirements to SWETOs: protect tunnel users, fire and rescue personnel, serve as rest areas and equipment storage and other.
    - Performance criteria for SWETOs in road tunnels, e.g., floor area pr person, breathing air, fire resistance, distance between shelters, etc. in relation with the system in which they are incorporated.
    - Design loads: What scenarios are reasonable for the design of SWETOs and the emergency preparedness system? What factors affect the design loads (FFFS, FRS' response time, interconnected SWETOs, traffic restrictions, etc.)? What scenarios are relevant in the future (energy carriers, digitalization, automation, malicious attacks, etc.)?
- Improve understanding of the efficiency of technical safety solutions, especially the combined systems' effects: There is a lack of data to evaluate the performance on new technologies, e.g., new materials, wayfinding systems, handrails, signs, distance between exits, etc.
- Improve understanding of dependency between technical systems, for instance cooperation between smoke management and design of SWETOs and cooperation between FFFS' and SWETOs.
- Smoke management strategies for evacuation systems including SWETOs. There is a need to develop functional requirements to the smoke management system to cope with scenarios that may occur and the need to support dynamic emergency response tactics. There are major uncertainties associated with the performance of smoke ventilation systems in road tunnels, and how flexible the systems are with regards to dynamical emergency response tactics.
- What is the appropriate distance between SWETOs? How can we obtain the appropriate distance between protected occupants and the fire, also if the fire spreads from its initial origin? What is the appropriate distance between SWETOs and groups of ventilators? How does new wayfinding technology impact requirements to distance between exits?

What are the regulatory constraints?

- Human behavior in fire situations is an essential starting point for design: Existing tunnel fires are important sources of information, which includes NSIAs' reports and international tunnel fire investigations. Fires and incidents which has not been investigated by the NSIA is also of major importance. The TCC has a real time overview of many Norwegian road tunnels through camera systems. This data should be utilized actively and systematically to learn from events. Research, which include evacuation experiments and virtual reality studies, are also relevant to investigate. We need to know more about how passengers affect the behavior of the drivers and how they all interact as agents of the system, consequences for users with reduced mobility and the safety-potential associated with professional drivers. Occupancy in underground shelters needs considerations, e.g., using affordance theory or user perception of underground space (UPUS), c.f. section 8.1.
- Operation and maintenance: Experience show that there are challenges associated with operation and maintenance in road tunnels. SWETOs introduce new equipment and system complexity, which affects operation and maintenance. There is generally a need to design new solutions for efficient operation and maintenance. Furthermore, new evacuation concepts need to come with convincing operations and maintenance plans.

10.4 The pilot projects as a knowledge-generation tool

The NPRD have initiated two pilot projects that included exceptions to the prohibition on "shelters without an exit leading to escape routes to the open". The tunnel owners, Agder and Trøndelag county municipalities, are obliged to participate in a follow-up R&D project after the tunnels have been built. Experiences from the pilot projects should strengthen any initiative to change the regulations on this matter and improve safety in Norwegian road tunnels.

The pilot projects represent "living labs", where we can focus on both single and comparative cases. The projects represent an opportunity to approach and raise the awareness of specific actors important in the tunnel safety management, and study interactions between technology, actors, and safety performances. The two islands connected to shore with the tunnel provide a splendid opportunity to address a stable population, in which tests, for example related to knowledge and evacuation competence could be designed.

There are several issues not particularly resolved by current strength of knowledge. With focus on the specific actors, some issues are raised below:

Tunnel users:

- What are the distribution and contents of the tunnel users' preparations, recognition, and response to emerging situations?
- How can the communication between various tunnel users and "teachers/authorities" be designed to increase situation awareness, referring to critical events in tunnels?
- How can situation awareness related to emerging fires become improved, and time spent on recognition reduced?

Tunnel control centers (TCC):

- What is the optimal distribution of automatic versus manual control of tunnels?
- Introducing a performance/event-based approach to tunnel fire management, what are the major critical phases for the TCC-operators in their crisis management?
- How can a safety management system influence TCC-operators' practical work, and

could it reduce workloads?
- To what extent need the TCC-operators to improve competence to work actively as controllers in a system-based approach to safety?

Call centers of the emergency services – 110, 112 and 113:
- Introducing a performance/event-based approach to tunnel fire management, what are the major critical phases for the 110-operators in their crisis management?
- Co-operation between actors will be facilitated by the call-centers, how can the call center improve conditions for the evacuees?

Tunnel owners:
- What are the appropriate requirements to the safety documentation for the pilot projects?
- What are appropriate scenarios for the design of the safety control plan?

Tunnel managers:
- Test design criteria: use the existing road tunnels and SWETOs to conduct experience testing with tunnel users to test the appropriateness of selected design criteria.
- Functionality of SWETOs will be maintained by effective safety control functions. How can tunnel managers work with a set of constraints and proper follow up activities to ensure expected functions of the evacuation systems.

Fire and rescue services (FRS'):

- How does the new evacuation concepts affect emergency response tactics?
- How can the co-operation principle influence design of training programs?

Interactions between actors:
- How can the pilot projects support preparation for future accidents and emergency response cooperation and learning across the involved actors?
    - Creating cooperative emergency drills that include the equipment in the tunnel.
    - Creating arenas for reflective thinking about tunnel safety.

10.4.1 Study on the use of SWETOs in road tunnels

There are limited specific studies on the use of SWETOs in road tunnels, which is natural considering the prohibition. The construction of SWETOs in the Flekkerøy and Frøya tunnel, and the existing SWETOs in the Oslofjord tunnel, represent opportunities to study the effect of associated systems for detection, notification, wayfinding, signage, user-instructions, and communication with occupants. It is also possible to study how the interior design affects usability and how the specific construction perform in full-scale fire tests and/or other accident loads, notably toxic releases, and explosions. Extreme fires are a major concern for the design of SWETOs, which should be investigated in a specific study. Both theoretical studies and experiments should support development of robust fire protection solutions, e.g., stand-alone fire walls with extreme fire resistance, or combined systems of walls and an active cooling system that together provide extreme fire resistance. Tunnel owners need to arrange a system for data collection to better understand the effect of SWETOs in road tunnels. Data from both crisis situations and normal state operation is relevant.

Both pilot projects, Flekkerøy and Frøya, are novel projects. Known processes and decision criteria do not apply equally well as in "standard" tunnel projects. The requirements to produce trustworthy documentation on the safety performance of the concepts are likely to become higher. If the pilot projects are supporting an initiative to change regulations, the documentation will become subjected to a higher degree of scrutiny.

A safety study could include considerations of several elements which are highlighted in this study, e.g., functional requirements, performance requirements of involved actors, dimensioning scenarios, alternative emergency response tactics, interactions in cooperative emergency response situations and requirements to design. The study should be designed to generate general knowledge, but the concepts and context of the available pilot projects would serve as case-studies to illustrate real challenges, scenarios, and emergency response capacities.

The study should build on systems thinking, in line with Directive 2004/54/EC, and a futuristic perspective, with an aim to design and develop safety control plans (for operation and maintenance) for the two pilot projects.

Beyond the benefits of the pilot projects, the study contributes to the major topics in terms of affecting future policies, improve understanding of systems thinking and active safety management, raise methodological issues on safety management, and add new knowledge to design and engineering processes.

10.4.2 Raise awareness: Information and education of local tunnel actors

The owner of many Norwegian tunnels – the Norwegian Public Roads Administration (NPRA) – has only to a limited extent distributed information about the fire risks in tunnels. As such, information about what to do in emergencies (self-rescue) in tunnels has been scarce. In December 2019, the NPRA launched a national PR campaign for the first time. The campaign consisted of six different videos with instructions on what to do in emergencies, reaching out to the youngest drivers, adult drivers, and truck drivers, by utilizing social media, such as Instagram, Snapchat, and Facebook. The videos were also used in connection with drivers' education. Recent studies by Knapstad (Unpublished) show that information campaigns have a positive effect on tunnel safety behavior, but a lasting effect prerequisite repeated exposure and reflective thinking. The pilot projects represent an important opportunity to raise awareness among the actors involved in the tunnel system. Hence, the following activities are suggested:

- Develop educational program for professional drivers in the area, i.e., drivers who regularly drives through the Flekkerøy and Frøya tunnels.
- Develop information campaigns directed at road tunnel users in the area, i.e., a "know your tunnel" program.
- Develop an educational program directed at local driving schools and learning drivers, highlighting the specific features of the local tunnels and appropriate behavior in emergency situations.
- Consider developing a tunnel simulator game for local tunnel users, which includes, e.g., a 3D model of the tunnel, ability to move around in a virtual reality environment, add an accident scenario and simulate consequences, etc.

10.4.3 Longitudinal studies to study the effects of local learning activities

The establishment of two SWETO pilot projects and the associated initiatives to reinforce its functionality, provides an opportunity to measure the long-term effect of information and education measures towards the local communities and professional drivers, as well as investigating the effect of cooperative activities among the involved actors, e.g., emergency drills.

A longitudinal research study that follows the pilot project would consider the specific context, measures, and tunnel actors' (drivers, cyclists and pedestrians, HGV drivers, TCC operators, first responders, 110-112-113 operators etc) learning over time. A control group should be established and followed-up for comparison and to isolate the impact from the measures associated with the pilot projects. A carefully designed research project could produce results that are in demand both nationally and internationally.

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12 Appendixes

Appendix 1: RISE Fire Research. Fire scenarios and thermal impact on evacuation shelters.

Appendix 2: Multiconsult. Summary of workshop on SWETOs, April 12th, 2023 in Oslo and Evacuation Shelters – Introductory Considerations of Geotechnical Issues and Proposal of Alternative Methods for Evacuation.

REPORT

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Fire scenarios and thermal impact on evacuation shelters

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Abstract

This chapter is about the thermal impact on evacuation shelters in tunnels. The thermal impact is related to the heat release rate (HRR) of the burning vehicles. There is numerous data available on HRRs for vehicles that can burn in tunnels, but information about the heat flux and therefore thermal impact from such vehicles is limited. In this chapter the fire dynamics behind how vehicles burn and how it influences the surroundings close to the fire is presented. The focus is on the vicinity of the actual fire, but there are also examples given for the thermal impact further away from the fire. The vehicles studied are both conventional vehicles, large and small, as well as alternative fuel vehicles. The chapter gives an overview of fire scenarios and thermal impacts based on theoretical fire dynamic relations and fire experiments obtained by the authors as well as other scholars. The maximum thermal impact is related to the maximum ceiling gas temperature at 1365 °C, which is reached for HRRs in the order of 100 MW.

Introduction

Vehicle fires

Vehicle fires in tunnels differ from vehicle fires in the open. The main difference is the influence of natural or mechanical ventilation flow as well as the geometry and type of surrounding enclosures such as walls and ceilings. When a vehicle starts to burn, the fire is initially dependent on access to fuel, i.e., the combustible materials. As the fire grows inside the vehicle, it may become controlled by ventilation and access to oxygen. The ventilation rate may also influence the flame tilt and thereby the fire growth rate inside the vehicle and fire spread to vehicles downstream. This is the basis in all fire physics, independent of the type or location of the burning vehicle.

In a Heavy Goods Vehicle (HGV) truck (with a trailer), if the engine under the driver cabin starts to burn, the flames need to break through the cabin floor or on the side of the driver cabin in order to get into the cabin, where much combustible materials is located. A key factor is also the openings, i.e., if the windows break it provide access to oxygen. If there is a natural or mechanical air flow inside the tunnel, i.e., wind along the tunnel, this may enhance the spread, but the later fire development will be dependent on if it blows in the direction from the driver cabin, or if it blows in direction towards the front of the driver cabin. When the fire has spread from the engine and into the driver cabin, the cabin becomes engulfed in flames and the windows break. If the wind blows in the direction from the driver cabin the fire will probably not grow further and the total HRR is limited to 2-5 MW. On the other hand, if the wind blows in the direction towards the front of the driver cabin the risk for fire spread towards the trailer behind it increases considerably. If it spreads the HRR can vary from 30 – 200 MW (see Fig. 1), depending on the cover of the trailer unit, the amount of combustibles inside the trailer and the length of the trailer [1]. The time to reach a peak HRR varies from 8 – 18 minutes. The fire may also start on the side of the trailer, for example due to overheated brakes which ignite the tires close to it. Then the fire spreads to cargo, but, again, the fire development will be highly dependent on the position of the fire and the wind direction as the fire spreads mainly through deflection of flames. Higher velocity usually deflects the flame more, and then the fire spreads along the trailer, and the HRR increases rapidly. There are also numerous blockages inherent in HGV vehicles which can create wakes behind them and thereby lower the wind velocity considerably. Examples of such blockages are the driver cabin itself, the front gable of the cargo wall (solid material) or the back doors to the trailer unit. All these parameters, i.e., access to combustible materials and its flammability properties, wind direction and speed, openings, wind shields, lengths, and heights among other things, will govern the final HRR and the resulting heat flux from the fire, e.g., towards an evacuation shelter.

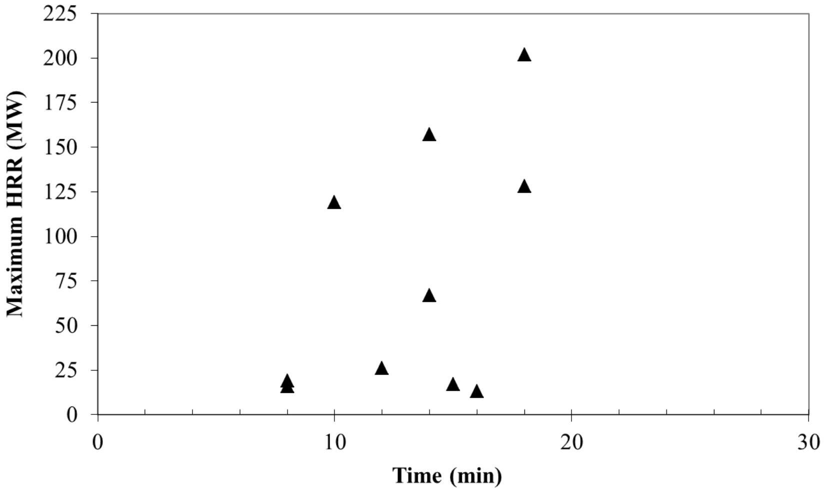

Figure 1 Summary of peak HRR versus time to reach peak HRR for HGV fire loads [1].

The HGV can sometimes be regarded as a Dangerous Goods Vehicle (DGV) due to the characteristics of the cargo. Usually, DGV consists of hazardous liquids or materials that are not “normal goods”. The fire size from DGVs is in the order of up to 400 MW, e.g., the petrol tank fire in the Skatestraum tunnel in 2015 in Norway [2]. The fire growth rate, if the fire becomes established in the highly flammable cargo, can be very rapid. The fastest growth rates are related to collisions in one way or another. In the Skatestraum case the trailer part collided into a wall and started to leak. The leakage was downhill along the pavement and into the drainage system. The petrol ignited and created a flame stripe about half a kilometer long at the same time as the trailer was engulfed in flames. This situation is extreme and may need to be considered in the design of shelters. The time duration is usually shorter, but the level of heat flux is enormous. The gas temperature in the vicinity of the fire was estimated to be about 1365 °C, which corresponds to heat fluxes around 390 kW/m^2, which is the highest that can be measured in tunnel fires [1]. There are also cases where the total HRR from multiple HGVs involved in the fire has become as high as for a single DGV. In the Mont Blanc fire 1999, the maximum HRR was estimated to be in the range of 300 - 380 MW with 15 HGVs involved, the Tauern tunnel fire in 1999 was estimated to be in the range of 300 – 400 MW and 16 HGVs involved and in St. Gotthard tunnel 2001 the maximum HRR was estimated to be 100 – 400 MW and 13 HGVs involved [1, 23]. This shows the potential of the maximum HRR when multiple HGVs become involved in the fire during the incident. The ventilation conditions did not limit these fires. It is not possible to add single HGVs and sum up the HRR. The time aspect of the fire spread and fuel consumption for each HGV needs to be considered [1].

In tunnel fires with forced ventilation the likelihood for an under-ventilated fire is low. The upper HRR limit can easily be estimated with knowledge of geometry and ventilation rate [1]. The largest estimated fire size is about 400 MW in the Skatestraum tunnel fire in 2015 in Norway with a tanker. With cross-sectional area between 50 m^2 and 100 m^2, and velocity of 2.5 m/s or more, the maximum heat release rate that is required before getting ventilation controlled is between 400 MW to 800 MW, respectively, see eq. (2.20) in [1].

In the case of a bus the situation is quite different compared to an HGV fire. Buss fires are usually not larger than 25 – 50 MW at the most. A conventional and alternative fuel bus has the same structure and about the same fire load. The body of the bus can be made of anything from plastics to aluminum or reinforced fiber material that burns relatively slowly. The interior, e.g., seats, burn easily and the fire spread thereof becomes rapid as long as there is oxygen available. In a conventional powered bus, the fire usually starts in the engine compartment in the rear end of the bus. The engine compartment is fire protected and, in many cases, there is an extinguishing system installed. The risk of fire spread is not very high for most buses, but if the fire spread to the passenger cabin there will be several factors that determine the fire development. A bus fire has many similarities to a building compartment fire except the large portion of glazed windows and the wall material that is different. Initially the compartment fire is dependent on the availability of oxygen. When the fire is developing inside the compartment, a two-zone smoke layer is created inside. The gas temperature in the hot smoke layer varies from some tens of degrees up to 100 ˚C. The fire at this stage is very local, maybe one or two pairs of seats or some area of the floor. The fire growth is mainly dependent on the flame volume created by the fire. There are no or limited effects from the tunnel wind flow at this stage. When the gas temperature in the hot smoke layer increases to over 100 ˚C it starts to radiate towards the floor, seats, and window. There will be temperature gradients in the glazed windows and when the gradient exceeds a critical value, the window will break. At this stage the smoke has spread along the entire bus and is still increasing. If no windows break the fire will not develop further. Closest to the fire, the windows will most likely break first, and oxygen supply will increase locally. If the windows start to break further away, we will have an increase in the HRR and gas temperature. The fire will burn through the ceiling if the body is made of reinforced fiber glass or plastics and if the temperature reach over 660 ˚C an aluminum body will melt down and create an opening. As more windows break the fire (flame volume) increases and involve more and more seats and floor material. The fire can at this stage not burn in the hot smoke layer in other parts of the bus due to the low oxygen levels. It requires more openings in order to continue. When all the windows or openings in the ceiling are established, the entire bus becomes engulfed in flames and maximum HRR is obtained. Now the wind in the tunnel starts to influence the fire development. Depending on the length and width of the bus, and if it is double decker or not, the HRRs will become around 25 – 50 MW. The number of performed fire tests for buses is less than 5 in the world. The measured time to reach a peak HRR has been found to vary from 7 – 14 minutes. The highest measured HRR in buses is 34 MW, but estimation show that it can be higher[1].

A single passenger car is usually limited to 2-8 MW, and up to three passenger cars around 8 – 16 MW. The time to obtain peak HRR varies between 8 – 55 minutes (see Fig. 2 [1]). The mechanism of the fire development is similar to the one in an HGV driver cabin or a passenger bus. The access to flammable material such as seats, interior and exterior plastics material in combination with access to oxygen are vital in this process.

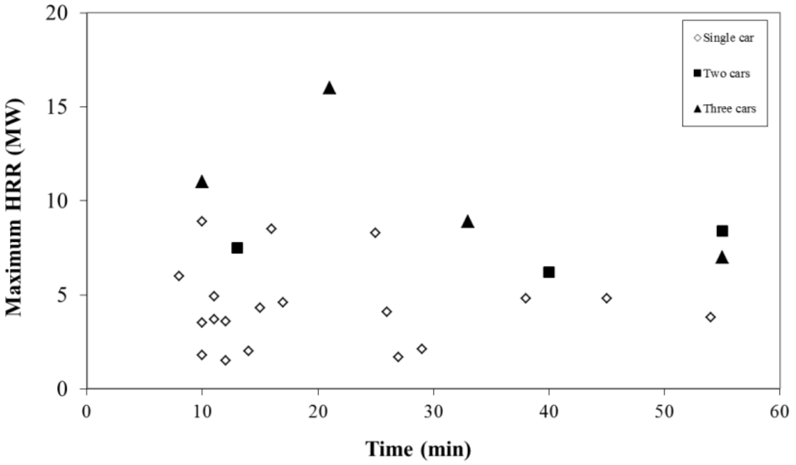

Figure 2. Summary of peak HRR versus time to reach peak HRR for single, two- and three-vehicle fires (passenger cars) [1].

The driving force in fire spread between burning vehicles in tunnels is the HRR of the first burning vehicle, the wind velocity and the tunnel width and height, where the tunnel height is more important than the width. In HGV fires, it has been measured that up to 70 – 100 m downstream a second HGV could start to burn [3]. In recently published research by RISE a model to predict the fire spread between vehicles has been developed [4]. The main feature of the study shows the critical conditions for fire spread to the second and the third objects. Comparison with test data showed that an average excess temperature of 465 K (or an equivalent incident heat flux of 18.7 kW/m^2) could be used as the criterion for fire spread, and this was verified further by other model-scale and full-scale tests.

The total released energy in different types of vehicles varies. For HGVs that have been used in fire test it varies from 10-240 GJ. In buses it varies between 41-44 GJ and in ICEVs between 2.1 – 8 GJ [1]. The radiation or heat flux from fires can be estimated by different models. This can be a point source model or a view factor model considering the potential radiation power of the burning vehicles. The point source model assumes that one third of the total heat release rate is radiated equally in all directions and decay as inversely proportional to the square of the distance from the fire. The potential radiation power model considers the radiative size relative distance using view factors to distribute the incident radiation. These models are presented in chapter 10 in Tunnel Fire Dynamics [1] and will be used later in this chapter to determine the thermal impact towards evacuation shelters at different locations from the fire and type of vehicle.

New Energy carriers

New energy carriers can be classified into liquid form, gas form or batteries [5, 6]. Liquid fuels refer to fuels that are stored in liquid form at normal temperature and pressure (NTP), such as ethanol. Gaseous fuels refer to fuels that are in gas phase at NTP. Here a distinction needs to be made between the following three types of gas storage.

1. Compressed gas in pressure vessels at high pressure, e.g., CNG @ 200 bar or hydrogen @ 700 bar.
2. Pressure-condensed, i.e., gases that condense at a certain pressure and thus is stored as a liquid, e.g., LPG @ 15 bar.
3. Cryogenic, i.e., gases that are cooled below the boiling point and stored as a cryogenic liquid in well-insulated containers, e.g., LNG or liquid hydrogen @ 4- 10 bar [7].

Vehicle gas storages are protected by a pressure relief device (PRD) that, e.g., in the event of fire, should release the gas before the container ruptures. Vehicle fuel safety is regulated by the United Nations Economic Commission for Europe (UNECE). For instance, CNG vehicles are regulated by UNECE R110 where a bonfire test should be conducted to ensure that the tank does not burst in the event of fire. Despite this, pressure vessel explosions has occurred without that the thermal melt-fuse released (TPRD) [8]. One reason for this has been attributed to local fire exposure of composite tanks that do not reach the TPRD. This has been verified in field tests [9]. Explosion incidents has also occurred for LPG vehicles [6]. These incidents has led to more stringent requirements (UNECE R134 and GTR[1] 13) for hydrogen vehicles [10, 11] including a local fire test and innovative explosion-free composite tank design [12].

Finally, electric vehicles (EV) refer to vehicles that make use of traction batteries such as lithium-ion batteries for their propulsion. Although EV fires often end up in the media, such fires are rare, about 5 to 20 times less probable than a fire in a ICEV [13]. EV fires that start in the traction battery are exceptionally rare. However, it should be noted that statistics so far are scarce and that the share of old EVs is much lower than the share of old ICEVs.

Impact from new energy carriers on vehicle design fires

For passenger cars, the energy carrier makes up a fairly small portion of the total HRR. Most fuels including LPG, CNG and LNG contain 20 – 50 MJ per kg fuel [14]. Hydrogen contains 142 MJ per kg but is limited by a very low energy per volume stored gas. One unit volume of compressed hydrogen gas @ 700 bar pressure contains about one seventh and liquid hydrogen about one quarter, the energy of petrol [15]. Typically, the amount of fuel is calibrated to give a suitable driving range which results in a similar total fuel energy content between different types of vehicles. For electric vehicles a similar trend can be seen. In the ETOX fire tests, two full-sized vans, one EV (40 kW battery) and one ICEV (44 l diesel), measured in total (including fuel and vehicle) 5.2 GJ and 5.9 GJ respectively (6 - 7 MW) [13]. The fire duration was similar, around 60 min in total, but in general, liquid fuel tanks burst after two minutes of fire exposure (according to UNECE regulation) and traction batteries can take very long time to become involved, which means the fire duration could be longer for EVs, which also means that the EV HRR would be lower (since the total energy content is similar). A thermal runaway that propagates from cell to cell yield the longest battery fire, usually below one hour for most traction battery packs, but up to 3 hours for some type of batteries [16]. An EV fire and thermal runaway that starts in all cells simultaneously (not very likely in real situations) lead to faster and more pronounced EV fires. For instance, EV tunnel fire tests performed by Sturm et al. [16] lasted for 15-30 min with peak HRR at 7 – 10 MW. For gas vehicles higher HRR peaks are possible. A gas jet flame from a 5 mm TPRD result in a calculated HRR at 34 MW and 100 MW for CNG @ 200 bar and hydrogen @ 700 bar respectively [14]. However, the incident thermal radiation from jet flames has in field experiments been measured to be low, below 5 kW/m2, a few meters away from the flame [9, 17]. It should also be noted that the tank pressure and the resulting HRR drops quickly and that the trend is to use smaller TPRD openings on these types of compressed gas tanks [12].

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[1] Global Technical Regulations

In sum, the total energy contained in the fuel does not differ widely between different types of vehicles. For most light vehicles it will be in the order of 1 - 2 GJ. Therefore, many vehicle fires will look the same regardless of the fuel. What can differ with different fuels is how fast or slow the energy is released, which is very dependent on the fire scenario. For most vehicle fire scenarios, liquid fuels, may start, or will contribute earlier. Gas fuels are more safely stored but can burn faster and even result in an explosion. Batteries are difficult to ignite and can burn for longer time. For loaded HGVs the impact from the energy carrier has an even smaller share of the total energy content.

Impact on response time for rescue services

Fires in electric vehicles could last longer and are more difficult to extinguish. However, if the battery becomes involved (i.e., thermal runaway), and is not extinguished, it will burn out completely within a few hours or less. Then the battery contains no energy and cannot re-ignite. Initially there was great concern with hydrogen fluoride (HF) being produced from battery fires (and vehicle fires in general). From an evacuation perspective there are several acute toxic gases present regardless of the type of vehicle burning, e.g. CO, HF, HCl and SO_2 [13]. From a rescue service perspective HF from battery fires has been shown to be a minor problem since their personal protective equipment offers good protection against HF [18]. Fires in gas vehicles inside tunnels are more problematic from a rescue service point of view. The Swedish civil contingency agency (MSB) have issued guidelines stating that 40 m or more upstream and downstream of a fire exposed gas tank is considered a prohibited area [19]. This means that the rescue service, with the current means, will not manage to make an offensive intervention, but will need to await that the gas vehicle burns out and then wait to ensure the tank is either empty or has been cooled and regained its strength before they can approach the vehicle. Such a defensive approach will take longer time to carry through, several hours or more.

Tunnel fire dynamics

The knowledge about fire dynamics in tunnels has increased greatly in the last ten years. In 2006 one of the authors presented a chapter on fire dynamics in tunnels [20]. This was the first time such textbook compilation of tunnel fire dynamics at the time was published. Later, in 2015, a complete textbook on Tunnel Fire Dynamics [1] was published. This contained over 400 pages of the latest knowledge. Since then, there has been a rapid increase in journal papers presenting new knowledge on fire dynamics in tunnels, especially from the mainland of China. This is related to the expansion of the infrastructure in China and that the authorities have made it possible for many Chinese universities to establish new research projects in this area. The main methodology has been numerical studies and model scale studies. Large full-scale tests have not been present such as in Europe and the US, where in the last decade numerous large-scale tests have been undertaken, mainly to test different types of extinguishing systems. In earlier full-scale tests and in the latest Chinese studies, the main focus has been on ventilation and the dynamic effects of it. A presentation of some of the main results on tunnel fire dynamics follows.

Ventilation

The main focus of tunnel ventilation research is on critical velocity and backlayering lengths. Much of the presented models have been developed in model scale but verified in large-scale tests. The model scale test varies from 1:20 to 1:3 in most cases. The focus of the large-scale tests (1:1) are usually on the fire size and model scale tests on temperature, fire spread and ventilation. The correlations between large scale tests and model scale tests become better as the scale ratio goes up, but for ventilation the scaling gives very good agreement. Using scaling in fire engineering has been known since early seventies and made it possible to develop many correlations used for calculations in tunnel fire dynamics. The scaling technique has also been known since early 1900 for fluid dynamics of boundary flows and development of ships and airplanes.

The critical velocity is dependent on the tunnel geometry (height, width, slope), the fuel height and the heat release rate. These correlations are often given in a non-dimensional form giving them a unique possibility to vary only few variables during testing. The most known equation is the Kennedy equation presented in the NFPA 502 standard. The correlation is based on large scale and model scale data but have come under discussion due to recently discovered effects of wind blockages on the results compared to model scale tests using no blockages. There is still no consensus on this subject but hopefully there will be in the near future. The second variable that is often discussed is the calculation of the backlayering length. The reason is that the rescue services need to get access to the fire from the upstream side, and therefore the amount of backlayering needs to be limited. The use of *critical velocity*, which in principle means no backlayering at all upstream the fire, and a *confined velocity*, with some allowed backlayering, varies between countries. The critical velocity depends highly on tunnel height, and up to a certain size the heat release rate. The critical velocity can vary between 2.5 m/s up to 4 m/s. In Norway earlier it was assumed that, in the case of a fire, a constant velocity up to 3- 4.5 m/s should be directed in the direction from the portal with a fire brigade arriving with better capacity towards the portal where the fire brigade with low capacity was arriving. This philosophy has been revisited and reviewed in recent time. In recent years there has been a change in the ventilation philosophy during evacuation. Lower velocities are preferred, or 2 m/s in the early phase of the fire, or until the emergency service arrive. It is the emergency service that determine the level of ventilation and its direction [21]. The risk with the older philosophy is that long portions of the tunnels can be smoke filled and if the ventilation direction is suddenly changed it may harm those who are evacuating in the previously smoke free part of the tunnel. This happened in the Gudvanga tunnel fire in 2013. The Gudvanga tunnel had longitudinal ventilation and, in accordance with the emergency response plan, the predetermined ventilation was 1–2 m/s during the evacuation phase, before the emergency service arrives. This applies regardless of where in the tunnel the incident/fire occurs [22].

When the heat release rate exceeds a certain value and depending on the tunnel height, it no longer influences the critical velocity. With a tunnel height between 5-7 m, the corresponding values are 10 MW and 20 MW, respectively. This means that most tunnels in Scandinavia obtain critical velocity at 3 m/s and 3.6 m/s, respectively. This means that fires in tunnels with less than 3 m/s may obtain some backlayering. For example, a passenger car (5 MW) burning in a 5 m high tunnel and 2 m/s ventilation will obtain 38 m backlayering length. This means that the rescue service can expect some heat flux from the smoke in the ceiling towards them when attacking the fire. The critical heat flux for fire fighters is often said to be 5 kW/m^2. This can be calculated when the backlayering length is known.

It is not always optimal to achieve the longitudinal critical ventilation velocity in tunnel fires. On the downstream side there are many things that can occur compared to if ventilation is limited. Imagine that there is almost no wind inside the tunnel. The hot gases from the fire rise towards the ceiling and after hitting the ceiling they spread in both directions along the tunnel. Due to the buoyancy of the hot smoke layer the smoke gas layer starts to propagate slowly along the ceiling. At a given distance the smoke has cooled down so much that the smoke gas layer descends to the level where road users are escaping from the fire. In the case of no ventilation this will occur on both sides, and depending on the heat release rate this distance can vary up to several hundreds of meters. If fire ventilation is started, this distance will be shortened considerably on the upstream side of the fire, and on the downstream side the turbulent smoke gas layer is mixed with the air down to floor level and may affect escaping people. Initial fire ventilation must consider the conditions of evacuees. The smoke layer height and the gas temperature in combination with the toxic gas concentration dictates the tenability.

In the case when the fires become very large there is a risk that the fire spread between vehicles. This depends on the tunnel geometry, ventilation, and heat release rate. When the gas temperature in the ceiling and in the front of the hot smoke gas layer (flame front) is over 450°C there is a risk that a second vehicle can ignite spontaneously. This increases the risk for fire spread and longer fire duration. The best example of this situation is the Mont Blanc and the Tauern tunnel fire with many HGVs involved. The flame length can be easily calculated by correlations developed in [1]. For example, a 100 MW HGV fire in a tunnel with a longitudinal ventilation of 2 m/s and 5 m height and 10 m width will have a flame length of 17 m downstream the fire. This means that a second vehicle within 17 m downstream the fire will ignite. The smoke backlayering will for the same situation be 55 m, so the situation on both side of the fire are quite challenging for the fire rescue services. To minimize the tunnel fire risk and these types of conditions, the use of Fixed Fire Fighting Systems (FFFS) has increased in the past ten years.

Fixed Fire Fighting Systems (FFFS)

The use of FFFS in the EU and US has historically been difficult for tunnels. Until around 2010 very little or no acceptance from authorities was experienced. The main reason was tests carried out in the Ofenegg tunnel in 1965 in Switzerland. These tests had a major impact on the use of FFFS in Europe. The main reason were some adverse secondary effects in the vicinity of the fire. The visibility was reduced, and the gasoline fuel reignited (hot spot far away) after the system had extinguished the fire and a deflagration occurred. Later research has shown that the adverse effects are difficult to obtain and today FFFS are more or less accepted in most countries. After the large fires in the Alps in early twentieth century the water mist industry saw the potential in installing high pressure systems with small droplets in road tunnels. They did their own large-scale tests and some large European research projects were started at the same time period. This development has led to an increased acceptance of this type of systems, and this is also reflected in standards such as NFPA 502 or guidelines based on the EU UPTUN project or German SOLIT project.

In Sweden all new major road tunnels will be equipped with FFFS and some older tunnel will be refurbished with FFFS to increase the fire safety. In 2013 and 2016 the Swedish Transport Administration (STA) went in lead to install a new type of FFFS in tunnels that are based on sidewall throwing systems with large drops instead of high pressure systems. The cost was reduced, and the systems were regarded as more robust, and it was possible to combine it with water supply for the fire brigade. The concept has been successful in operation and is planned to be installed in other countries [23].

One of the advantages with FFFS is that there is a possibility to make trade-offs with other technical systems. Example of such trade-off is to reduce the fire protection of the construction. Also, the heat release rate is reduced and the risk for evacuees is decreased, especially in the case of HGVs or DGVs. The ventilation strategy can be made easier using FFFS, i.e., the system makes the fire less sensitive to higher ventilation rates, and even can dilute the toxic conditions downstream the fire [24][26.

In 2018 the STA decided to investigate the possibility of using automatic sprinklers in tunnels. One of the tunnels south of Stockholm is a typical bi-directional Norwegian fjord tunnel with a slope of 5 % and a height difference of 60 m from the bottom and up to the portals. Tests in 1:3 scale were done using fully automatic sprinklers. The system was able to control large fires such as 100 MW HGVs and the influence of the ventilation were found to be less than expected. There is a limitation to the use of such systems in tunnels with high ventilation rate but in tunnels with ventilation rates below 2 m/s before the fires starts, this type of system is a good alternative [25].

One important feature of FFFS is that it can effectively cool down the surface temperature of structures. Sprinklers are sometime used to re-classify products by installing spray sprinkler heads that cool the exposed surface of products such as glazed windows. The water spray is an effective surface cooler and could be very effective in colling the surface temperature of a wall construction exposed to heat fluxes from large fires. Lundqvist [26] and Göras [27] has measured the cooling effects of fire wall products in order to find the optimized water flow hitting the wall on the non-exposed side. The water spray from sprinklers is something that can be used and investigated as a potential measure to reduce the risk with thermal heat flux to doors or walls adjacent to evacuation shelters.

Thermal impact on evacuation shelters

Regarding evacuation shelters equipped with oxygen and overpressure, the design variables are the air/smoke tightness of the shelter walls and doors, and the thermal impact and its fire resistance and the number of evacuees that can use it. These evacuation shelters can also be named rescue room or self-rescue room. It can be an evacuation shelter mounted into a larger blasted space into the side of the tunnel wall at different distances. The measures of these evacuation shelters may vary but in for example Moscoso et al [28] measures of 5 m wide and 10 m deep with a height of 2.4 m is used as minimum]. The design of an evacuation shelter may vary, but in this chapter, we assume a wall exposed towards the tunnel space made of 10 cm and 15 cm, respectively, thick concrete wall (5 m x 2.4 m) equipped with a fire steel door (1 m x 2 m) with 7 cm thick insulation. The results from the calculations can be easily updated when more accurate information is available.

There is a possibility to calculate the thermal exposure towards a shelter depending on the distance to the fire, the fire size and ventilation. If we assume there is a vehicle burning just outside the evacuation shelter, then we can calculate the thermal exposure towards the wall adjacent to the evacuation shelter and its door. The maximum incident heat flux, as stated earlier, can be up to 400 kW/m^2. The time it will take for the thermal wave to propagate through the wall can be calculated. Consequently, the time it will take to increase the temperature inside the wall to a critical gas temperature can be obtained. The critical gas temperature for humans can be regarded as 70 °C for a shorter period. These values are dependent on the exposure time. That in turn is dependent on the fire duration, its fire development, and the fire rescue response.

The fire development for different vehicles varies but single vehicles seldom burn for longer than one hour [1]. If there is a situation such as in the Mont Blanc tunnel 1999, with multiple HGVs vehicles involved in the fire, the incident heat flux towards the wall will be felt not only from the fire beside the shelter but also from the other vehicles burning at the same time but further away. If most HGVs burn for about one hour, the most intensive incident heat flux will be during the time the vehicle beside is burning. The fire will continue towards other vehicles but the contribution towards the wall will be reduced as the fire travels away from the wall. The next shelter, depending on the distance between the evacuation shelters, will eventually start to experience heat flux towards the wall. The probability for such scenario in Norwegian tunnels, such as occurred in the Mont Blanc tunnels, should be regarded as low.

In the following a calculation of the incident heat flux to the wall, depending on the position of the HGV that is burning, is given as an example. An HGV fire of 20 MW, 50 MW and 100 MW will be used for the calculation.

Incident heat flux to evacuation shelter

The maximum ceiling gas temperature as a function of the distance x (m) and maximum gas temperature (°C) at fire location gives the incident heat flux towards the evacuation shelter. The maximum ceiling gas temperature can be obtained by the following equation (for low ventilation) [1]:

$$T_{g,\max} = T_a + 17.5\frac{Q^{2/3}}{H^{5/2}} \qquad V' \leq 0.19 \qquad (1)$$

$$T_{g,\max} = T_a + \frac{\dot{Q}}{u_0 b_{fo}^{1/3} H_{ef}^{5/3}} \qquad V' > 0.19$$

Where

$$V' = u_0 / w^* = u_0 / \left(\frac{g\dot{Q}}{b_{fo}\rho_0 c_p T_0}\right)^{1/3}$$

and $\dot{Q}$ (kW), effective tunnel height H_{ef} (m), radius of fire source b_{fo} (m), u_0 longitudinal velocity in tunnel (m/s), and ambient temperature T_a (15 ºC) is in °C and T_0 is ambient in Kelvin. The maximum gas temperature (is 1365 °C, the temperature cannot be higher than that. If one obtains higher value with eq. (1) the gas temperature should be set equal to 1365 °C [1]. This means that heat release rates (Q) higher than the value given gas temperature 1365 °C, will yield the same values, independent of the MWs. For example, if 100 MW fire yields excess temperature of 1365 °C, a 200 MW or 400 MW would also do that.

The gas temperature decay as a function of the distance from the fire source is:

$$T_{g,x} = T_a + (T_{g,\max} - T_a)(0.55e^{(-0.143\frac{x}{H})} + 0.45e^{(-0.024\frac{x}{H})}) \qquad (2)$$

The incident heat flux towards the wall as a function of the distance from the fire can be estimated by the following equation:

$$\dot{q} = \sigma T_{g,x}^4 \qquad (3)$$

where σ is Stefan-Boltzman coefficient, 5.67 10-11 kW/(m^2 K^4) and $T_{g,x}$ is obtained from eq. (1) and (2). Consider the following example. A 20 MW, 50 MW and a 100 MW fire, respectively, is located in a tunnel with height 6 m. The effective height H_{ef} is 5 m as the fire is on a truck trailer (1 m up to fire load). The wind is assumed to be 2 m/s, so the influence of the ventilation needs to be considered for the 20 MW and 50 MW since $V' > 0.19$. For the 100 MW fire the upper equation in eq. (1) is used as $V' \leq 0.19$. In Fig. 3 the calculated incident heat flux as a function of the distance using eq. (2) and (3), for 20, 50 and 100 MW, respectively, are shown.

It is clear from Figure 3 that the maximum heat flux towards the fire wall (adjacent to the evacuation rooms inside the blasted space in the mountain), decay rapidly as a function of the distance from the fire. The incident heat flux is a maximum value as the gas temperature used to calculate the heat flux is the maximum ceiling temperature, and the gas temperature at lower levels is lower. This is a conservative assumption to do the calculation in such a way. Within 100 m from the fire the incident heat flux is reduced to 10 % or more of the maximum value. The velocity influences the stratification of the smoke. Increased stratification means that the high gas temperature and incident heat flux are mainly on the upper part of the door or walls to the evacuation shelter, while the lower part of the door or walls to an evacuation shelter is not directly exposed to such high gas temperatures as explained above, and the temperature is at a much lower level, which may be more like ambient temperature. . As the distance increases, say 10 times or more the tunnel height the smoke stratification starts to decay and the gas temperature at the ceiling become more similar to the rest of the cross-section at about 50 – 100 times the tunnel height. This is a rough estimation but gives reasonable estimation of the conditions in a tunnel with ventilation, say 2 m/s or less. Higher velocity tends to destroy the smoke stratification earlier than with low velocity. Thus, Figure 3 gives a reasonable safe estimate of the incident heat flux as a function of the distance. This incident heat flux can be used to calculate the wall or door temperatures in an evacuation shelter as a function of time.

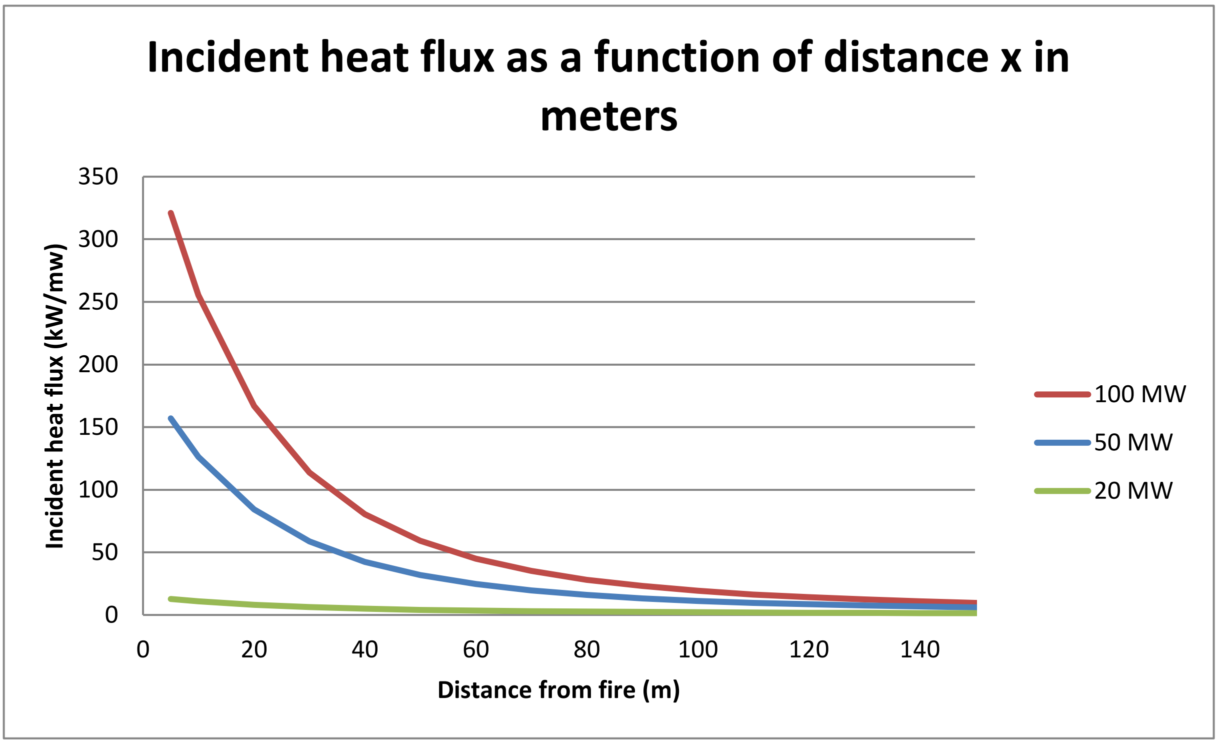

Figure 3 The incident heat flux as a function of the distance x from the fire for a 20 MW, 50 MW and 100 MW fire, respectively.

The maximum incident heat flux towards an evacuation shelter is if the fire is located just beside an evacuation shelter (x=0 m). This would mean that the maximum possible incident heat flux is about 400 kW/m^2. This is the case when 100 MW fire is used as design fire. For 50 MW design fire this will be 195 kW/m^2 and only 15 kW/m^2 for the 20 MW fire. The reason is that the incident heat flux is a function of the gas temperature up to the fourth power times Stefan-Boltzmann constant (eq. (3)). The gas temperatures for the 100 MW fire are 1365 °C, 1103 °C for the 50 MW and only 455 °C for the 20 MW design fire. A reasonable assumption done in fire conditions with very high gas temperatures is to assume that the wall surface temperature does not differ from the exposed gas temperature. This assumption will make it easier to use analytical solutions to calculate the temperature increase inside the wall. In the following such calculations is presented.

Time of penetration of heat wave through wall and door adjacent to an evacuation shelter

It is possible to calculate the penetration time and the temperature variation in the fire wall or door adjacent to the evacuation shelter. This can be done by using the first boundary conditions presented on p. 266 in reference [1] (eq. 10-71). These calculations assume a thick wall (thermally thick wall), and the one dimensional heat equation is solved analytically according to the following equation.

$$T(z,t) = T_a + \left(T_{g,x} - T_0\right) erfc(\zeta) \qquad (4)$$

Where $a_w = \dfrac{k_w}{\rho_w c_w}$, $\zeta = \dfrac{z}{2\sqrt{a_w t}}$ and z is the distance from the surface of the material w. The full heat penetration time can then be estimated to be (16% raise of the exposed gas temp):

$$t_p = \frac{\delta^2}{4}\frac{\rho_w c_w}{k_w} \qquad (5)$$

The above equation can be used to approximately estimate the temperature inside a thermally thick wall at a location where the thermal penetration has not occurred. However, after the full thermal penetration, the backside temperature, T_{bw}, plays a significant role and the heat flux towards the shelter becomes:

$$\dot{q}_{tot} = \dot{q}''_{wb}\, A_w = \frac{k_w}{z_w}(T_{g,x} - T_{bw}) \qquad (6)$$

Example of calculation using eqs. (1)-(6).

We assume a design fire of HRR=100 MW, u_o=2 m/s, T_o=15 °C and the fire is located just beside the fire wall adjacent to the evacuation shelter (x=0 m). We assume a Fast growing fire up to 100 MW. The Fast growing fire has the following expression:

$$\dot{Q}(t) = HRR = \alpha t^2 \qquad (7)$$

where α is equal to 0.047 kW/s^2 or 0.169 MW/min^2 (Fast fire growth rate). This means it will take 24.3 minutes to obtain 100 MW and after that it will be maintained constant up to 1 hour. Using eq. (1), we obtain the following time – temperature curves shown in Fig. 4. If the evacuee shelter is 100 m or 50 m downstream the fire eq. (2) can be used with eq. (1) as input for HRR=100 MW. In Fig. 4, the gas temperatures as a function of time for a Fast fire up to 100 MW at x=0, x= 50 m and x=100 m, respectively, is given for a tunnel that is 6 m high and 10 m wide.

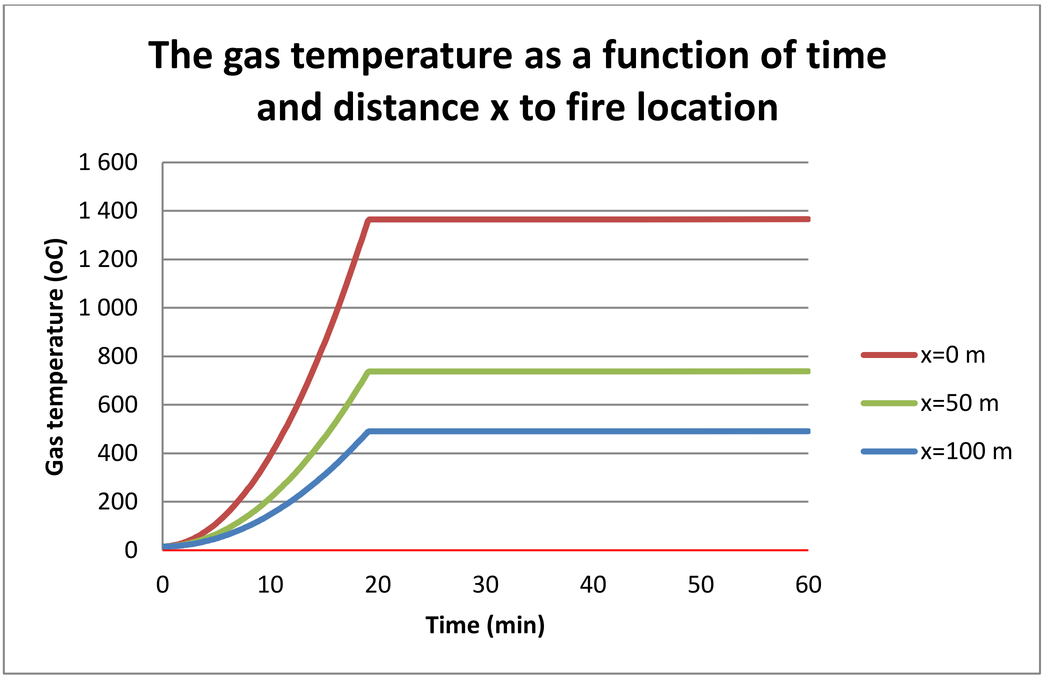

Figure 4 The gas temperature as a function of the time for a Fast curve up to 100 MW.

In Fig. 5 the resulting temperature inside an insulated steel fire door is shown using eq. (4). Note that this equation is presented for the first boundary condition (a fixed surface temperature). However, in the calculations, the time-varying temperature curves in Figure 4 were used. For example, when we calculated the inner surface temperature at 30 min for a given location, the gas temperature at 30 min was used, assuming that the structure had been exposed to such a temperature (peak value of the corresponding curve) for 30 min which is clearly conservative from this point of view.

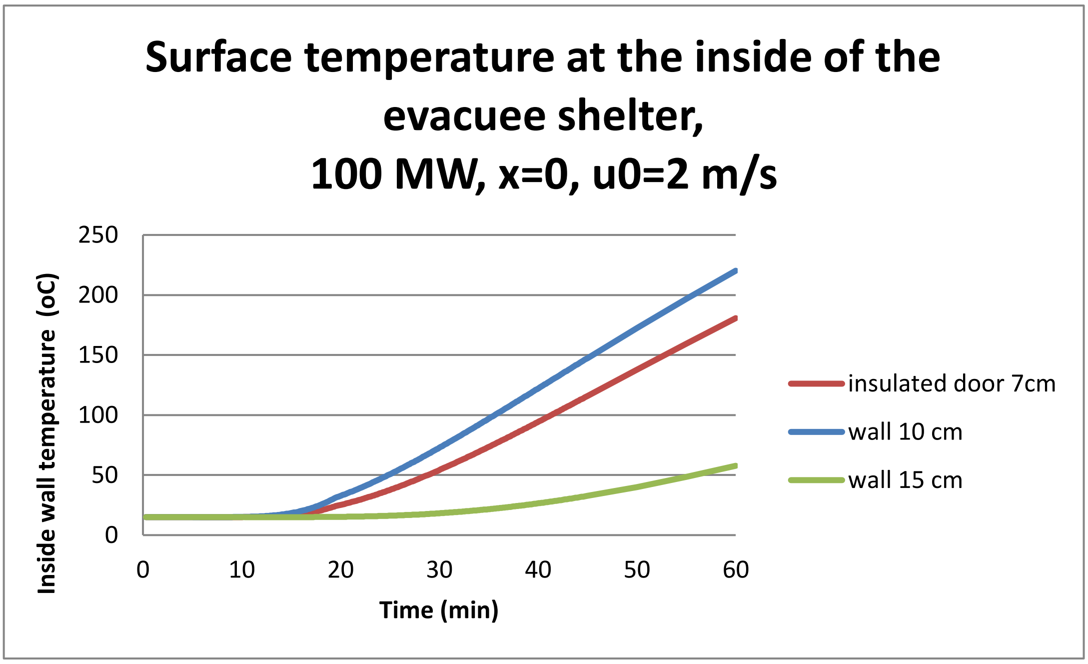

Figure 5 The inside surface temperature at a 7 cm insulated steel fire door and a 10 cm thick concrete wall exposed to a Fast design fire up to 100 MW. A surface temperature of a 15 cm thick concrete wall is also plotted.

The concrete wall is assumed to have k_w=1.37 W/m °C, ρ_w=2300 kg/m^3 and c_p=880 J/kg K [29]. The steel door with fiber insulation board are assumed to have the following values k_w=0.048 W/m °C, ρ_w=240 kg/m^3 and c_p=700 J/kg K [29]. By using eq. (4) we can obtain the temperature as a function of time at the distance z equal to the wall thickness for different products and thickness. This is an approximation as the wall is regarded as semi-infinite. The heat wave penetration time according to eq. (5) becomes 71 min for the door and 61 min for the 10 cm wall at respective z distance from the exposed surface. The wave penetration time for 15 cm concrete wall is 138 min according to eq. (5). The expected accuracy is under 16% according to this simple model and calculation. The temperature at the given distance z show us that the temperature at the inside of the wall adjacent to the evacuation shelter is around 180 °C after about 60 minutes for the insulated door. Corresponding values for a 10 cm and 15 cm concrete wall are 220ºC and 57ºC respectively. The maximum heat flux according to eq. (6) is therefore 15.6 kW/m^2. This heat flux can be used to calculate the heating of the evacuation shelter.

For classification of building products that are tested and exposed to ISO time – temperature fire curves, the criterion is 180 °C, for an average of 5 points measured at the surface on the non-exposed side, and the corresponding time to obtain this average temperature defines the classification of the product. This is an example, but it shows that such an extreme fire as 100 MW fire just beside the fire wall adjacent to an evacuation shelter can withstand the heat wave up to 50 minutes for a 10 cm concrete wall and 60 minutes for an insulated steel door that is 7 cm thick. A concrete wall of 15 cm thickness or more can withstand this heat exposure with some margins.

Although surface temperatures at 180 °C of the wall on the inside may appear to be high, the evacuation shelter may be situated some distance from the wall with an air lock in between. In Statens vegvesen report [30] a solution using a steel container placed inside a larger space blasted into the tunnel side walls with an air lock connected to the steel container and a fire wall with door and concrete wall exposed to the tunnel is presented. The surface temperature of the concrete wall, which was 20 cm thick, was estimated to be in the order of 380 °C in that report. The calculation was based on steady state condition for the heat wave, which yields higher values than obtained in the dynamic study presented herein. An interesting result from the report is that the air lock gas temperature was found to be in the order of 29 °C for a 100 MW fire. This shows that the wall temperatures obtained above, would not compromise the tenability for evacuees inside the shelters.

Discussion

Within risk analysis fire scenarios may be derived. The thermal impact from a road tunnel fire mainly depends on the HRR which in turn depends on what is burning, i.e., car, bus, or HGV, where an HGV or DGV fire can result in the largest HRR. The energy carrier does not have a significant impact on the HRR. The maximum ceiling gas temperature at 1365 °C becomes dimensioning for thermal impact for HGVs or DGV scenarios for HRRs in the order of 100 MW, or more, depending on the tunnel geometry and ventilation conditions. This means that even for a 200 or 400 MW fire with growth and decay within 1 hour, the thermal impact can still be managed with standardized solutions. However, an increased use of alternative fuels, such as hydrogen, would imply an increased transportation of such fuels by DGV, which also need to be considered, although the long-term viable transport solution for hydrogen is by pipeline [15].

The fire duration for a single vehicle fire last for up to 1 hour. Longer fire durations, c.f. Mont Blanc, is possible if the fire can spread to vehicles downstream. Key factors for fire spread are HRR, wind, and tunnel height. HGV fires can spread up to 50 m downstream in 2-3 m/s wind. How likely the fire is to spread will depend on the HRR, the type of tunnel (e.g., uni- or bi-directional), the amount of vehicles (AADT) and mitigation measures, e.g. mechanical ventilation or a FFFS, if available.

The time until the rescue service can make an intervention depends on the size of the fire, ventilation conditions, and the type of cargo or energy carrier that is involved. If the fire does not spread, most ICEV fires burn out within 1 hour. For battery electric vehicles they might want to let the battery to burn out rather than extinguishing it, which could take slightly longer time. For fire exposed gas tanks, the rescue service might choose to take a defensive tactic, which could take several hours to carry out. If the fire spreads to more vehicles the intervention will be more resource intensive and time consuming, c.f. Mont Blanc.

Within the scope of this chapter, we find that two key uncertainties are: whether or not fire spread occurs and what tactic the rescue service would adapt if gas tanks were exposed to fire. Fire spread is dependent on the wind speed in the tunnel which to some extent can be controlled with fans. A sprinkler system would significantly limit the risk for fire spread and the thermal impact on wet surfaces including evacuation shelter boundaries would be negligible. However, with a sprinkler system the need for evacuation shelters in the first places is much reduced since fires will be smaller. In the future, explosion-proof gas tanks that start to leak before they burst would reduce the second uncertainty. RISE have tested such tanks that handled both local fire and extinguishment with water that cooled the TPRD. In all tests the gas leaked slowly through the material in a controlled way.

Simulation tools such as FDS are being widely used to study tunnel fires. They cannot accurately be used to simulate vehicle fire development inside road tunnels but could be used to estimate the risk for further fire spread to other vehicles. For this purpose, there are also hand calculation equations available.

For a given a certain fire load, the thermal exposure and the resulting heat propagation via a wall or door into an evacuation shelter can be calculated. Example calculations herein shows that standard heat resistance solutions result in tenable temperature conditions inside the evacuation shelter.

Future research needs

Tunnel fires are often described in one dimension, e.g., through the maximum ceiling temperature or smoke stratification upstream or downstream the fire. However, close to the fire they are in essence three dimensional in the sense that cold air is entrained on both sides of the fire along the tunnel wall and there could be a significant temperature difference between the floor and the ceiling. For the thermal impact on evacuation shelters, this is important as the thermal impact is lowered to some extent by the cold air along the side wall as well as the colder air temperature some distance below the ceiling where, for instance, the door to the shelter is positioned. In a future study these effects could be investigated using CFD, small or large scale tests. A large scale test could also serve to demonstrate that evacuation shelters handle real and severe tunnel fires.

The emergency intervention concept to firstly push the smoke in one direction to assist tunnel users in evacuation shelters on the fresh air side, and next reverse the flow and push the smoke in the opposite direction and assist the remaining tunnel users on the other side deserves some research. Firstly, this way of using the ventilation contributed to the large fire spread to several vehicles on both sides of the original fire in the catastrophic Mont Blanc tunnel fire [31, 32]. Maybe not only tunnel users but also vehicles would need to be evacuated before the ventilation is reversed? Secondly, depending on the fire size and its location relative to the tunnel inclination it may not be possible to reverse the ventilation flow due to massive buoyancy forces, a plan B would then be needed.

At the time of the tragic alpine tunnel fires and the introduction of the EU directive on minimum tunnel safety in 2004 [33], FFFS was not an option for tunnel safety, however, that situation is today very different. Efficient and economically viable FFFS for rural tunnels could be researched, similar to recent developments in Sweden where sprinkler systems for large city tunnels as well as smaller rural sub-sea tunnels have been developed [23]. FFFS in road tunnels could reduce the installation costs for evacuation shelters if the requirements for thermal insulation are lowered. A systematic investigation of the benefits of FFFS in relation to evacuation shelters could be a future research topic.

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NOTAT

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1 Introduction

This memo is a summary of data collection based on expert discussions through 1) workshop and 2) geotechnical engineering considerations.

The first part of the memo includes a summary of a workshop held in Oslo April 12th, 2023, focusing on evacuation shelters in long single tube tunnels. This includes a description of the methodology employed during the workshop as well as a summary of all presentations held. This memo also summarizes the group discussions during the workshop. From the discussion summary several hypotheses have been formulated. This is to highlight areas where available knowledge is deemed insufficient to form a sound decision basis for revising regulations regulating the use of evacuation shelters in long Norwegian single tube tunnels.

Secondly, this memo includes a geotechnical engineering note describing different geotechnical considerations related to the construction of evacuation shelters in existing single tube tunnels. This topic was not part of the scope during the workshop, but is still considered relevant, especially when considering the cost-effectiveness of constructing evacuation shelters as an alternative to emergency exits in accordance with relevant regulations.

2 Purpose

The purpose of the workshop, and the geotechnical engineering note, was to gather existing knowledge and determine how to approach topics, questions and possible solutions that should be further investigated. The aim is to establish an appropriate plan for studying the viability of evacuation shelters in long single tube tunnels. A central part of establishing this plan was a segment during the workshop focusing on discussing what knowledge is necessary to challenge existing regulations banning the use of evacuation shelters. The workshop also allowed for learning about completed projects deemed relevant for further studying the use of evacuation shelters, and also explored the possibility of aligning and coordinating both ongoing and planned projects and studies.

A central focus of the expert discussion was to map expectations regarding the use of evacuation shelters in tunnels. This included:

- What topics are deemed central when establishing a decision basis regarding evacuation shelters?
- What topics need further investigation to establish the decision basis?
- What ongoing projects include evacuation shelters as part of the tunnel’s safety concept?

The purpose of the expert discussion was not to identify and describe various solutions. Rather, the experts were asked to identify areas where there is a lack of knowledge, and where further studies or other activities are deemed necessary to establish a decision basis for revising the regulations banning the use of evacuation shelters.

3 Method

The workshop consisted of two main segments. The first segment focused on introducing all participants to studies and knowledge considered relevant for the following discussion (the second segment). This included presentations on ongoing pilot projects where evacuation shelters are being constructed in Norwegian tunnels, introduction to fire dynamics in tunnels, evacuation systems and possible psychological reactions tunnel users might experience during a crisis in a tunnel.

Following the presentations, the participants were divided into four groups. Each group was tasked with discussing a predefined topic related to the use of evacuation shelters in long Norwegian single tube tunnels. The participants were asked to assume a situation where the use of evacuation shelters is permitted and to reflect on the changes that had been implemented to reach this situation.

The topics being discussed was:

- Regulation
- Evacuation shelter design
- Operations and maintenance
- Control measures and restrictions

For each topic, one person was tasked with facilitating the discussion and documenting key takeaways. After approximately 1-1,5 hours the groups rotated, so that each group focused on two topics. The concluding segment of the workshop was a plenary discussion where those responsible for facilitating the discussions summarized what had been said, allowing the rest of the participants to add or elaborate on what had been discussed.

After the workshop, several hypotheses were derived from the discussion. These hypotheses are meant to describe areas or topics where the participants thought available knowledge is insufficient and more studies are necessary. The backdrop for deriving these hypotheses is to establish a sufficient decision basis for revising existing regulations banning the use of evacuation shelters in long Norwegian single tube tunnels.

To ensure that both the presentations and the following discussions were of high quality it was important to involve a wide range of experts within the tunnel safety field. A criterion for selecting participants for the workshop was familiarity with aspects related to operations, maintenance, design, and research concerning evacuation shelters. User-oriented expertise, such as representatives from the heavy vehicle industry, the Norwegian Association of Disabled and the Norwegian Automobile Federation, were not represented during the workshop. The intention is to conduct a separate workshop including user-oriented aspects to a greater extent at a later stage. Further, participants from contractors were not represented during the workshop. Hence, constructability was not a major topic during the workshop. To compensate for this, a geotechnical engineering note is presented at the end of this memo. The note presents various aspects related to constructability concerning evacuation shelters in existing tunnels.

Table 1 lists all workshop participants. Several of the participants represented KATS-project, which is an abbreviation of *Kapasitetsløft Tunnelsikkerhet,* translating to Capacity Boost Tunnel Safety in English.

Table 1: Workshop participants.

Name	**Organization**
Bjørn Arild Fossåen	The Norwegian Public Road Administration, Directorate of Public Roads /KATS
Inger Lise Johansen	The Norwegian Public Road Administration, Directorate of Public Roads
Sverre Kjetil Rød	The Norwegian Public Road Administration, Directorate of Public Roads / KATS
Helge Gilberg	The Norwegian Public Road Administration, Directorate of Public Roads
Thorbjørn Hetlevik	The Norwegian Public Road Administration, Directorate of Public Roads
Ole Christian Leerstang	The Norwegian Public Road Administration, Traffic Control Centre South
Haakon Stokkenes	The Norwegian Public Road Administration, Traffic Control Centre East
Anine Kalmo Larsen	The Norwegian Public Road Administration
Terje Sundfær	Trøndelag county municipality
Bernt Olav Opheim	Trøndelag county municipality
Hallvar Hotvedt	Aas Jakobsen
Jan Øyvind Pedersen	Agder county municipality
Trond Sinnes	The Norwegian Public Road Administration, Directorate of Public Roads
*Sonja Lindqvist	Ministry of Transport
*Stian Sommerseth	Ministry of Transport
Liv Rørlien	Road Supervisory Authority
Kenneth Vik	Rogaland Fire and Rescue Services / KATS
Jonas Bråten	Follo Fire and Rescue Services
Tommy Ueland	Directorate for Civil Protection and Emergency Planning
Frits Johansen	Directorate for Civil Protection and Emergency Planning
Bjørnar Raaen	Multiconsult/KATS
Micol Pezzotta	University of Stavanger / KATS
Geir Sverre Braut	Stavanger University Hospital / Western Norway University of Applied Sciences / KATS
Henrik Bjelland	University of Stavanger / KATS
Ove Njå	University of Stavanger / KATS
Gunnar Jenssen	Sintef Mobility/KATS
Are Holen	NTNU
Jonatan Gehandler	RISE/KATS

**Participated during the first segment (presentations)*

4 Presentations

The program of segment 1 is presented in Table 2. First, Inger Lise Johansen made an introduction of the ongoing pre-study, namely its background, major issues and further works. Second, there were presentations associated with three existing road tunnels where evacuation shelters are on the agenda. The aim with this section was to present variations in how evacuation shelters are designed in Norwegian road tunnels, experiences with operations and maintenance and challenges in the design process. Third, Jonatan Gehandler from RISE gave a summary of relevant research and knowledge gaps within tunnel fire research. Fifth, Gunnar D. Jenssen from Sintef summarized research activities associated with evacuation shelters and self-rescue in road tunnels conducted at Sintef. Finally, Are Holen discussed human responses to crisis situations and reflected upon transferability of knowledge to road tunnel accidents. The short presentations were intended as a backdrop for the following group discussions.

Table 2: Program of presentations in segment 1

Time	Topic	Presenter
10:00 – 10:30	Welcome, brief presentation of participants, today's program Information about the project and relevant background.	Henrik Bjelland, University of Stavanger Inger Lise Johansen, the Norwegian Public Road Administration
10:30 – 10:55	Central solutions from pilot projects – the Flekkerøy tunnel and the Frøya tunnel	Jan Øyvind Pedersen, Agder county municipality Terje Sundfær, Trøndelag county municipality
10:55 – 11:10	Experiences from operations and maintenance of evacuation shelters in the Oslofjord tunnel	Anine Kalmo Larsen, the Norwegian Public Road Administration
11:10 – 11:25	Tunnel fires	Jonatan Gehandler, RISE
11:25 – 11:40	Experiences from VR studies, literature study and evacuation systems	Gunnar D. Jenssen, Sintef
11:40 – 12:05	Evacuation and possible psychological reactions	Are Holen, Norwegian University of Science and Technology
12:05 – 12:15	Introduction to table discussions	Henrik Bjelland, University of Stavanger

The following is a summary of the presentations held during the first segment of the workshop.

4.1 Evacuation shelters without an exit to the outdoors – Work forming a basis for possible revision of existing regulations

- By Inger Lise Johannesen (Norwegian public road administration)

The Norwegian Tunnel safety regulation (2007) implements the EU-directive 2004/54/EF into Norwegian law. The regulation applies to all tunnels on the Trans-European Transport Network as well as other national roads longer than 500 m. There is also a corresponding regulation for Norwegian county roads. The Tunnel safety regulation specifies that appropriate emergency exits shall be constructed if a risk assessment considers it necessary. In addition, tunnels with a traffic volume exceeding a yearly average of more than 4000 vehicles per day shall be constructed with emergency exits. However, constructing emergency exits without an exit to the outdoors is prohibited. Hence, the Tunnel safety regulation bans the construction of evacuation shelters in new and existing tunnels.

This ban could imply that evacuation shelters contribute negatively considering the safety of tunnel users. Based on previous fire incidents, the Accident Investigation Board Norway has criticized the lack prerequisites for upholding the self-rescue principle in long single tube tunnels. Due to several fire incidents in the Oslofjord tunnel, the construction of evacuation shelters in the tunnel was permitted in 2012. However, this was to be considered as a temporary measure, until a new tunnel tube was constructed. In 2017, two tunnel users survived a tunnel fire by seeking refuge in one of the evacuation shelters. Therefore, the Norwegian Public Road Administration’s hypothesis is that evacuation shelters could be appropriate and cost-effective measures in long single tube tunnels. Consequently, it is desirable to consider revising the regulation and allowing the construction of evacuation shelters or grant exemption from the ban for certain tunnels. Part of the argumentation suggesting exemptions or revising the regulation is that the basis for the ban does not appear to be well-informed. Furthermore, significant technological advancements have been made, and new knowledge has been established since the ban was introduced in 2007. It is still necessary to establish and present evidence that proves that the use of evacuation shelters will strengthen the safety of tunnel users during an incident.

In 2020, the NPRA applied for permission to construct evacuation shelters without exits to the outdoors in long single tube tunnels. This would be an exemption under § 11 of the Tunnel safety regulation allowing the use of new technology or procedures that improve the safety related to a tunnel. This means that it is necessary to prove that the new technology provides the same or better level of safety compared to technology described in the regulation through risk assessments. During dialogue in the winter of 2020/2021, the Ministry of transport supported the process, but noted that additional knowledge was necessary.

As of today, the NPRA have granted exemptions to construct evacuation shelters in two existing long single tube tunnels under § 11 of the Tunnel safety regulation. A prerequisite is that both tunnels are to be considered pilot projects with the purpose of gathering knowledge and experience regarding evacuation shelters. The NPRA does not intend to grant new exemptions for other tunnels until more knowledge has been established.

The NPRA has initiated a preliminary project together with the University of Stavanger. The purpose of the project is to update existing knowledge as well as identify what studies are necessary to conduct to establish a sound decision basis for revising the Tunnel safety regulation. Future projects include the follow-up of the pilot projects. This includes gathering and systemizing knowledge and experiences from both tunnels in terms of operations and maintenance, tests and exercises, and incidents. Additionally, the NPRA intends to internationally call for tenders with the intent of gathering further knowledge to demonstrate that evacuation shelters are safe and effective safety measures.

4.2 County road 457 the Flekkerøy tunnel: Evacuation shelters – waiting rooms for assisted evacuation

– by Jan Øyvind Pedersen (Agder county municipality)

The Flekkerøy tunnel is a single tube subsea tunnel between mainland Kristiansand and the island Flekkerøy. The tunnel was constructed in 1989 and is approximately 2,3 km long. It has a gradient upwards of 10 % and is open for pedestrians and cyclists. The average daily traffic volume was approximately 4900 vehicles per day in 2021. Based on a risk assessment, it was considered necessary to implement additional risk reducing measures to ensure the safety of the tunnel users. Initially, a new tunnel tube was recommended. However, the cost associated with such a measure was considered too high, and therefore not considered further. As an alternative, prohibiting pedestrians and cyclists from using the tunnel was also considered. Such a restriction was not deemed possible as there are few options for this group of tunnel users getting to and from the Island Flekkerøy. Therefore, it was decided that three evacuation shelters should be constructed. The shelters will be evenly spaced in the tunnel with an approximate distance of 500 m. One of the shelters will be placed in the lowest section of the tunnel whereas the remaining two shelters will be placed in the ascending sections.

The shelters are constructed as containers located within excavated niches in the tunnel. A concrete wall will be constructed so that the container is separated from the tunnel tube. This wall will be protected from the impact of a vehicle collision and with a fire resistance equivalent to at least EI120. The wall will be constructed with a door that leads to the niche where the closed off container is located. The door handle will be made of a material that prevents tunnel users from burns when opening the door.

The containers will be pressurized to prevent smoke from the tunnel tube from entering the container. The container will be designed with airlocks where air supply inside the container is initiated when the innermost door is opened. The air supply will be sufficient to sustain 12 people for a period of a minimum of six hours. There will also be available power supply that shall last for six hours. The inside of the containers will be video monitored allowing the TCC access to live footage from each container. There will also be radio communication and speakers facilitating communication between the users of the shelters and the TCC-operators. Communication equipment may also be used by emergency services through the emergency control panels placed in front of each tunnel portal.

The shelters will be equipped with a toilet, and food and water. Additionally, air tanks and respirator masks will be placed in the niches where the containers are located. This equipment is meant to be used by fire fighters during the extinguishing of fire or when evacuating tunnel users inside the containers.

The shelters are included in the tunnel’s emergency preparedness analysis and -plan.

Due to the Flekkerøy tunnel being a mainland connection most tunnel users are locals that use the tunnel on a regular basis. Therefore, Agder county municipality (being the owner of the tunnel) considers it possible to involve the tunnel users during the project. This includes informing the tunnel users how the evacuation shelters function, as well as receiving feedback as to how the tunnel users perceive the use of the evacuation shelters. Agder county municipality will also gain knowledge related to the life cycle cost related to this type of evacuation shelters, such as costs concerning operating the shelters as well as maintenance. The pilot project will also further consider alternative use of the shelters, such as storage area for fire fighters’ equipment.

4.3 County road 714 Frøya tunnel: Establishment of evacuation shelters

– by Terje Sundfær (Trøndelag county municipality)

The Frøya tunnel is a 5,3 km long single tube subsea tunnel along the road *fylkesveg 714*. The tunnel was opened in 2000, has a width of 8 m and a maximum gradient of 10 %. The lowest section of the tunnel lies 164 m below sea level. The tunnel connects the island Frøya to the island Hitra, which is further connected with the mainland through the Hitra tunnel.

The Frøya tunnel is currently being renovated and upgraded, a project that includes the following technical measures:

- Lighting
- Video surveillance, including automatic incident detection
- Road shoulder and edge line
- Cables and cable suspension
- Navigational lighting
- Ventilation system
- Water supply
- Technical building and technical facilities
- Signposting
- Area outside of tunnel
- Tunnel vault
- Evacuation shelters

Based on the existing design of and safety equipment in the tunnel it was considered necessary to implement additional safety measures. As a result, it has been decided that 12 evacuation shelters will be constructed in the tunnel. The spacing between the shelters will vary from 340 to 500 m and shall give tunnel users that are unable to evacuate the tunnel by them self a room protecting them from heat and smoke. A risk assessment considering the construction of the evacuation shelters considers the shelters to increase the possibility for tunnel users to survive during scenarios where they would otherwise be engulfed in smoke or exposed to other harmful substances in the tunnel. Consequently, the shelters reduce the risks of serious harm to tunnel users and fatalities during large tunnel fires considerably. The risk assessment has also considered risks associated with shelters not functioning properly or used as intended during an incident. The assessment did not identify conditions or characteristics that indicate that risks associated with such errors outweighed their risk reducing effect.

The evacuation shelters will be dimensioned for 50 people for å minimum of 3 hours. The area of the shelters will be approximately 30 m^2, equivalent to 0,6 m^2 per person. This is based on the dimensioning of the existing evacuation shelters in the Oslofjord tunnel. Fresh air will be supplied through air tanks that the tunnel users have to operate. Instructions regarding how the tanks shall be operated will be provided inside the shelters. Further, the air supply will also provide an overpressure within the shelter, ensuring that smoke does not enter the shelter from the tunnel tube.

As opposed to the shelters constructed in the Flekkerøy tunnel, the shelters in the Frøya tunnel will not be constructed as containers. Instead, the shelters will be established as niches with exposed rock covered by a waterproofing membrane on walls and ceiling. This is considered to help in ensuring that the temperature inside the shelter does not get too high in the event of a tunnel fire. A door from the tunnel tube will lead into the airlock room where a second door leads into the shelter. The airlock shall prevent significant amounts of smoke from entering the shelter.

The evacuation shelters will be equipped with first aid kits, as well as speakers and an emergency phone providing a direct line to a TCC-operator. Surveillance cameras will also be installed in each shelter allowing a TCC-operator to monitor the situation in the shelter. Information boards will inform tunnel users how to communicate with the TCC, operate the air tank system, etc. The design of the information board is inspired by those used in the Oslofjord tunnel.

During the presentation the importance of involving the correct actors was emphasized. For the pilot project the NPRA, Trøndelag county municipality and TCC were considered as key actors. Further, informing and training tunnel users was regarded as crucial in ensuring safe and effective use of the evacuation shelters. An important part of this was effective communication between tunnel owner, the authorities, and the tunnel users. Lastly, the importance of thinking of evacuation shelters as part of a greater system was emphasized. Local emergency services, road section outside of the tunnel and technical safety installations were mentioned as examples.

4.4 Evacuation shelters in E134 Oslofjord tunnel

– by Anine Kalmo Larsen (the NPRA)

The Oslofjord tunnel is a subsea tunnel crossing the Oslofjord between Frogn municipality and Asker municipality along road E134. The tunnel is 7,3 km long with a maximum gradient of 7 %.

After a large fire in 2011 it was decided to construct 25 evacuation shelters in the tunnel. Some of the design criteria that were basis for the construction of the shelters were ensuring that tunnel users could safely use the shelters for three hours if the ambient temperature rose to 40 °C or for 1,5 hours if the temperature rose to 60 °C inside the shelters. Further, the concentration of CO_2 should not exceed 2 vol%, concentration of O_2 should not fall below 14 vol% and the concentration of smoke gas should not exceed 375 g min/m^3. The available area inside the shelters should be at least 0,4 m^2 per person.

Fire simulations determined several important factors/parameters that should guide the design and equipment of the evacuation shelters. The results showed that the size of the fire was of less importance compared to the time it took to extinguish the fire. The volume of the shelter was also of importance when determining the "residence" time. The volume of the shelter had to be increased by 50-80 m^3 for every additional hour tunnel users were to stay in the shelter. Alternatively, it was necessary to introduce fresh air (using air tanks) if the volume of the shelter was less than 180 m^3. The simulations also showed that the concentration of hazardous gas determines the need for air supply rather than the number of people inside the shelters. Additionally, high temperature inside the shelter was not considered critical, and the risk of hypothermia could represent a greater challenge.

The evacuation shelters were designed based on the established design criteria and the results from the fire simulation. As for the Frøya tunnel, the evacuation shelters in the Oslofjord tunnel are not constructed as containers, but rather as niches that have been walled in by 300 mm Leca blocks. An A120 fire resistant door leads through this wall and further into the airlock. The evacuation shelter is entered when exiting through the second door in the airlock. The shelters are equipped with an emergency telephone allowing for communication between tunnel users and a TCC-operator. Additionally, the shelters are equipped with camera detection, first aid kit and water. There is also a light indicator in the tunnel tube indicating if tunnel users have accessed the shelter. This allows for effective identification of which shelters are being used by emergency services during an incident.

20 out of a total of 25 evacuation shelters have been equipped with 80 l air tanks (with a pressure of 300 bar) lasting approximately 3,5 hours. These tanks are controlled once a month and changed at least once a year. The rest of the shelter is maintained/inspected 12 times a year. Camera service is carried out twice a year and the telephones are serviced once a year. In addition, electronics are randomly checked as well as a planned yearly functionality test.

There have not been reports of any major challenges concerning the shelters by operations & maintenance personnel, nor by the TCC. However, the high humidity inside the shelters has represented a challenge; especially concerning certain equipment subjected to corrosion. There are also issues regarding emergency communication network and cell phone reception.

To conclude the presentation, Kalmo Larsen told how the shelters had been used during a previous tunnel fire in the Oslofjord tunnel in 2017. Two tunnel users sought refuge in the shelters when a truck loaded with toilet paper caught fire. Both suffered mild burns on their hands when opening the door leading from the tunnel tube to the airlock. The air tanks were not used during the incident. The fire department entered the evacuation shelter 25 minutes after the tunnel users entered the shelter. They were told that it was safe to stay in the shelter, and that the fire department would return to assist them with evacuating the tunnel. After spending 30-40 minutes inside the evacuation shelter both tunnel users evacuated the tunnel, assisted by the fire department. During this time communication between the evacuees and a TCC-operator was established. In addition, both the first aid kit and the water available were used.

4.5 Tunnel fires and thermal exposure

- By Jonatan Gehandler (RISE Research Institute of Sweden)

Following the presentations on both pilot projects and the use of evacuation shelters in the Oslofjord tunnel, Jonatan Gehandler gave a presentation on fires in alternative fuel vehicles and fire dynamics in tunnels.

The presentation started with an introduction of typical fire characteristics of different types of vehicles. The following data is copied from the presentation:

Vehicle	HRR	Energy	Peak
Truck	30-200 MW	10-240 GJ	8-18 min
Bus	25-50 MW	41-44 GJ	7-14 min
Passenger car	2-8 MW	2-8 GJ	8-55 min

One of the alternative fuel vehicles that was mentioned was hydrogen-powered vehicles. One of the main concerns related to these types of vehicles is the possibility of explosion. Modern cars are equipped with pressure relief devices (PRD) designed to release gas before the tank ruptures. However, there have been instances where these PRDs have failed causing a lot of energy being released in a very short amount of time, consequently causing an explosion. Based on experiments, there is a recommended safety distance of 40 m if there is a risk of hydrogen tanks exploding inside tunnels. This complicates the efforts of the fire department, prolonging their fire suppression effort.

Also, electric vehicles represent certain risks not found in vehicles with internal combustion engines. For instance, a burning lithium-ion battery will produce a significant amount of hydrogen fluoride gas. It will also not be possible to extinguish a burning battery cell, meaning that any fire fighting effort should be focused on cooling the surrounding battery cells to prevent the fire propagating. Fire fighting effort should also focus on preventing the fire from spreading to nearby vehicles and structures/installations. The fire fighting efforts will also be prolonged due to the possibility of the fire reigniting several hours after the initial fire has been extinguished.

The presentation also focused on the characteristics of a tunnel fire making it more hazardous and challenging to manage compared to a burning vehicle on a stretch of road out in the open. The most obvious characteristic is that smoke and gas is not removed from the site of fire. Therefore, it is necessary to control the speed and direction of the smoke to facilitate the evacuation of the tunnel users as well as facilitate effective fire fighting efforts. This is because it is challenging to evacuate in the same direction as the smoke is ventilated, at the same time that the fire department requires wind in their back to access the fire site.

If there is no ventilation of smoke the smoke will stratify along the tunnel vault until it cools off and drops towards the road. Such a ventilation strategy could allow for the smoke to spread in both directions, making it difficult for the fire department to access the fire site. Alternatively, the ventilation system could be used to move smoke away from the fire site creating a smoke filled and smoke free zone in the tunnel, separated by the fire site. However, a longitudinal ventilation system could cause the fire to spread to other truck wagons or other vehicles close to the burning vehicle, mainly due to radiation heat transfer.

Lastly, the use of fixed fire fighting systems in tunnels was presented. Until 2010, the use of such systems faced low acceptance in both the EU and the USA. However, due to several tests and experiments in the last decade, fixed fire fighting systems have become common in tunnels in these countries where the traffic volume is high. These systems are mainly based on high pressure systems and the use of nozzles. Also, RISE and the Swedish Transport Administration have developed a low-pressure system.

4.6 Experiences from VR studies, literature study and evacuation systems

- Gunnar Jenssen (SINTEF mobility)

The sixth presentation focused on the results from a literature study concerning the use of evacuation shelters, as well as a VR study exploring what factors lead to the tunnel users finding and entering evacuation shelters. The VR study also focused on elements and technical solutions that make the use of evacuation shelters more acceptable for tunnel users.

The literature study examined regulations regarding the use of evacuation shelters or similar facilities for:

- Construction phase of tunnels
- Use in the mining industry
- Underground work facilities (civilian or military)
- Offshore oil installations
- High rise building

The requirements may vary from country to country and evacuation shelters may be fixed installations or be mobile. The use of evacuation shelters is prohibited in Norwegian road tunnels, as well as for other tunnels that are part of the Trans-European Transport Network. There are primarily two reasons why this ban exists: two people died in an evacuation shelter in the Mont Blanc tunnel in 1999, and a post-fire report stating that tunnel users will not seek refuge in these shelters unless they are guided by personnel.

The literature study notes that several tunnel users, including the two that died, found the evacuation shelters themselves without assistance. Reference is also made to the fire in the Oslofjord tunnel in 2017, where two tunnel users found their way to an evacuation shelter, which probably saved their lives. Both examples show that the conclusion drawn from the post-fire report concerning the Mont Blanc fire is misleading, and that people can find evacuation shelters and other emergency exits unassisted.

The study also uncovered some good and bad design aspects of both wayfinding systems and evacuation shelters. These include the location and number of shelters in the tunnel as well as capacity. All these design aspects should take into account local characteristics related to each individual tunnel. Lastly, alternative use of evacuation shelters was mentioned. Fire fighters will be able to enter these shelters during firefighting efforts to avoid the noise produced by the ventilation system.

The design and technical solutions of evacuation shelters are of importance to ensure that tunnel users are willing to remain in the shelters once they have entered. Some of these design criteria were determined through a VR study on 3D simulated evacuation shelters. Lighting is especially important for feeling safe, hence staying inside the shelters. Establishing different areas within the shelter also proved important. This means establishing separate areas for toilets, areas with beds for injured people etc. Participants of the VR study reported that the shelters became more legible and better liked. Participants also reported that they preferred speaker/phone placement right in front of the entrance door of the shelter. The visibility of speakers may be important for a better understanding of messages and thus create a better sense of safety.

4.7 Evacuation and possible psychic reactions

- Are Holen (Norwegian University of Science and Technology)

To better understand how tunnel users might react during an incident in a tunnel, the last presentation focused on the psychological reactions one might expect during a scenario where their life is threatened and there is an urgent need to evacuate the tunnel.

Some of the stressors that are expected to affect how tunnel users react during an incident includes smoke and fire, hazardous liquids or gases, the sight of a collision scene with injured people, etc. These stressors might lead to the tunnel user perceiving an incident to threaten their own or others life. People will react differently when exposed to these stressors, but typical effects include tunnel vision, less reasoning when deciding how to act and to a various degree confusion. Confusion is caused by situational factors and psychological causes, such as reduced visibility (due to smoke), reduced hearing (due to excessive noise) and reduced ability to navigate in the tunnel. How people react is typically divided into three categories:

- 10-15 % will function better during a crisis
- 70-75 % will depend on others to take charge. These people will follow the rest of the group or as they are told.
- 5-10 % may act irrationally and will not be able to evacuate without assistance. This group of people might experience paralysis or inaction.

Certain groups of people function better than others during a crisis. For instance, miners or offshore workers are expected to function better than others as these people have been trained and prepared to act in a certain way during specific crises. Being prepared for a crisis is negatively correlated to having severe negative reactions during a crisis.

If the tunnel users are not prepared for a serious incident in a tunnel, it is important that others “empower the survivors”. This includes warning the tunnel users and informing them about what is happening in the tunnel, how dangerous the situation is and what their alternatives are. Assisting the tunnel users in evacuating will reduce the probability that they experience inaction, where they do nothing. If the tunnel users are guided into evacuation shelters, it is deemed beneficial to inform them about the possibilities that the shelter provides and what they may expect until they are evacuated.

Once inside the evacuation shelters, it is possible that some tunnel users could experience anxiety and claustrophobia. It is therefore considered beneficial if the users of the shelters experience some level of control, which will reduce stress and confusion.

Lastly, the presentation emphasized the importance of emotional first aid after a serious accident. To underscore this point, it was mentioned that 60 % of people experiencing serious traumatization recuperate quickly, 15 % need a little bit more time, 13 % will relapse at a later stage whereas 12 % will suffer chronic conditions.

5 Table and plenary discussions

The group discussions from segment 2 of the workshop have been summarized below, sorted according to the following four topics:

- Regulation
- Evacuation shelter design
- Operations and maintenance
- Control measures and restrictions

Based on the discussion several hypotheses have been formulated. The purpose of these hypotheses is to highlight areas where the workshop participants deemed available knowledge to be lacking considering establishing a sound decision basis regarding revising the ban on evacuation shelters in long single tube tunnels.

5.1 Regulation

Pilot studies	
There are two ongoing pilot studies where evacuation shelters are being constructed in existing single tube tunnels. Protocols detailing what information that should be gathered in the event of an accident requiring tunnel users to use the evacuation shelters should be established. As of today, the NPRA have not established any requirements detailing what experiences and knowledge that should be gathered from these pilot projects. Nor are there any explicit expectations as to what empirical findings the NPRA considers necessary or useful to gather from these pilot projects.	**Hyp. 1:** A study should be conducted to identify and map out which experiences can be obtained from ongoing pilot projects to build evidence. **Hyp. 2:** We lack the knowledge as to how the pilot projects can enable us to build evidence. We also lack knowledge as to what may be considered evidence regarding evacuation shelters.
It is not certain that the two pilot projects are sufficient to convince EU that evacuation shelters are an effective safety measures in single tube tunnels. It should therefore be considered comparing the performance requirements of the pilot projects to those of the evacuation shelters in the Mont Blanc tunnel. This will allow for documenting that the shelters of the pilot projects are different from those unsuccessfully used in the late 90's and early 00's. The pilot projects are being established on the basis of the regulatory requirements, i.e., both are existing tunnels with no absolute requirements in regard to emergency exits. However, the tunnels differ in regard to characteristics indicating elevated risk levels for both tunnels. For both tunnels emergency exits have been suggested/recommended, but this has been dismissed due to significant costs. The evacuation shelters in both tunnels vary considering both layout and the systems surrounding the shelters. Also, the shelters vary in the extent they are designed according to recommendations from Sintef's studies.	**Hyp. 3:** It is not sufficient to determine whether evacuation shelters are valid safety measures based on empirical findings from two pilot projects. It is necessary to acquire additional information regarding the potential impacts of the pilot projects. It is also necessary to develop strategies to attain favourable results while preventing unfavourable ones. **Hyp. 4:** We lack an understanding of how knowledge gained from the pilot projects can be utilized. It is therefore necessary to systemize how both data and empirical findings from these projects are gathered and processed. This work should include how chosen solutions are rationalized, with emphasis on solutions related to Sintef's recommendations. **Hyp. 5:** There are no clear understanding of how worst-case scenarios related to evacuation shelters should be approached, both in general and for the pilot projects in particular. It is not certain how the evacuation shelters of the pilot projects (along with the surrounding systems) would perform during an extreme fire, such as the Mont Blanc tunnel fire in 1999.

Background and actors	
It is considered necessary to analyse the background for the ban on evacuation shelters in tunnels. Was the justification of the ban professionally and comprehensively supported? Was this strictly banning evacuation shelters or were other safety measures required instead or existing measures emphasized/enhanced? The ban is considered to contradict performance based regulatory regimes. Hence, banning evacuation shelters should be based on convincing evidence. In general, it is challenging to understand the basis for the ban, as there is limited supporting documents available. However, it is known that influential experts, especially in France, wanted the use of evacuation shelters to be banned.	**Hyp. 6:** Due to limited knowledge regarding the ban of evacuation shelters we have a limited ability to construct a comprehensive evidence-based argumentation that supports lifting the ban? **Hyp. 7:** We lack the knowledge as to how we can demonstrate that evacuation shelters are safe and effective safety measures. It is necessary to determine what tools may assist us in demonstrating the effectiveness of evacuation shelters, such as quantitative analysis, simulations, modelling, etc.
As this is considered to be the first time anyone is trying to lift the ban on evacuation shelters it is considered necessary to conduct an actor analysis. This will provide information about what actors are in a position to impact the legislation. How is the commission composed, and what mechanisms apply for changing the regulation. It is naïve to think that Norway singlehandedly is able to change the regulation. It is therefore of interest to understand which countries are considered relevant when seeking to revise the regulations. However, all countries should be able to impact revisions. Are evacuation shelters only relevant in Norway, or is it also relevant for the rest of the EU? In principle, the EU only has to be involved when considering tunnels that is part of TEN-T. Norwegian authorities are within their right to revise regulations concerning roads that are not part of the TEN-T. Three possible strategies have been identified: - Utilizing the leeway of the current regulation (possibility of exceptions as given by §11) either for individual tunnels or in general. - Implement exemptions for 2.3.4 in the regulation for only Norwegian tunnels. - Revise the regulation.	**Hyp. 8:** We lack knowledge as to what the opinion in Europe is today regarding evacuation shelters. Who needs to be convinced and what are the mechanisms that allows for revising the regulation? Are evacuation shelters only relevant for Norwegian tunnels or is there a perceived need in Europe as well?

Flexibility within current regulation: Exceptions under § 11	
The regulation is flexible in regard to using new technology in order to improve/assure safety in tunnels. This exemption provision is not considered fully applicable for evacuation shelters as it does not address total design, but rather has a reductionistic approach. However, the feedback from the Ministry of transportation is that the provision can be broadly interpreted. The Flekkerøy tunnel pilot project uses containers as evacuation shelters. This can be regarded as new technology in terms of a production and operations perspective. The use of Evacsound (in addition to other installations) allows for considering increasing distance between evacuation shelters. The Frøya tunnel pilot project does not apply new technology in terms of the evacuation shelters, but rather in terms of the concept. For instance, the pilot requires new procedures for controlling ventilation.	**Hyp. 9:** There is no clear definition of what is considered "new technology". It is therefore necessary to determine if the evacuation shelter concepts of the pilot projects may be considered new technology. In turn, this makes it necessary to study how relevant technology have evolved since the ban on evacuation shelters was introduced in 2004 (both in a broad and narrow sense).
The reference level for comparing the effect of evacuation shelters is not clear. Opinions vary, where some think that a solution including evacuation shelters should be compared to a solution that does not include such shelters, whereas others argue that the ban should be considered in a context where emergency exists is part of the solution, hence this should be the reference level for evaluating the effect of shelters. What the reference level should be might also vary depending on the tunnel being new (under design) or existing. In other words, evacuation shelters could be considered as better than no measures or as a cheap option to emergency exits. The latter could lead to evacuation shelter being adopted as a measure to avoid expensive (and more effective) measures. The fall pit of comparing the effect of evacuation shelters to no measures is that one could be left with unacceptable residual risk if the reference level already represented unacceptable risk. If this is the case, is it necessary to prove that the reference level (no measure) also represents acceptable risk? There are also risks associated with the use of cross-passage between tunnel tubes as doors may get stuck, people could pass through the door and into moving traffic. This goes to show how safety measures must be considered as a system in a broader sense, rather than individual safety measures. The tunnel system must also include parameters, characteristics, and other relevant factors outside of the tunnel. Further, existing Norwegian single tube tunnels are not in full compliance with existing regulations. Hence, one may argue that all risk reducing measures can contribute to improving the safety of tunnel users.	**Hyp. 10:** We lack an understanding of how to interpret "a level of protection equivalent to or higher than the technology established in the regulation". **Hyp. 11:** it is necessary to better understand whether the exception from the ban should be interpreted as an isolated exception, or if it should be evaluated in the context in which it is stated, i.e., requirements related to emergency exits.

Conditions for applying evacuation shelters as a safety measure	
Factors considered necessary for successful use of evacuation shelters should be investigated. This could include ventilation (longitudinal vs. transverse ventilation), restrictions (e.g., hazardous materials, possibility for bikers and pedestrians to use the tunnel), capacity of shelters in terms of how many people they should fit, general surroundings, factors related to emergency preparedness etc.	**Hyp. 12:** it is necessary to determine what conditions/prerequisites are necessary for successful use of evacuation shelters.
In a regulatory perspective it is important to consider whether evacuation shelters should only be allowed for existing tunnels where these shelters will give an unambiguous positive contribution to safety. One should act with more caution when considering allowing new tunnels to be designed with evacuation shelters, as this could be considered as a cheap option to more effective emergency exits. A tunnel's traffic volume should be closely considered when deciding whether evacuation shelters are a viable option. High traffic volumes increase both the probability and expected consequence of accidents. The complexity of introducing these shelters in tunnels with high traffic volumes is considered to be significant and therefore less optimal.	**Hyp. 13:** We lack an understanding of what is required of evacuation shelters for them to be considered viable and acceptable alternatives to emergency exits. To determine these requirements, it is necessary to consider the need for differentiating between new and existing tunnels.

How should a potential regulatory revision be formulated/implemented?	
It is necessary to consider if it is desirable to remove the ban or simply allow for exemptions from the ban. The latter would require the regulation to be more flexible. During the workshop there was consensus that completely removing the ban is not optimal. Hence, it is necessary to establish criteria or conditions that must be met before exemptions can be considered. For instance, is it possible to only make exemptions for existing tunnels where the traffic volume is lower than a certain value? Restrictions related to the length of the tunnel were not considered appropriate/relevant. If designing new tunnels with evacuation shelters is being considered it is important that these solutions are compared to solutions including emergency exits. One should be very careful when considering allowing exemptions from absolute minimum solutions such as double tubes and emergency exits. A dilemma arises when considering tunnels shorter than 10 km with a daily average traffic volume of less than 4000 vehicles per lane. It is also possible to accept certain exemptions in accordance with the regulations provision 2.3.5. A possible strategy of approaching possible exemptions allowing evacuation shelters could be the NPRA accepting evacuation shelters in existing tunnels with a traffic volume under a certain level, where emergency exits are geologically impossible. Several participants during the workshop considered increased use of exemptions where preferable to completely removing the ban as it is considered necessary to regard the entire tunnel system. If it is not possible to revise the EU directive, is it still desirable to revise the regulation concerning Norwegian roads that is not part of the TEN-T? It might be problematic for tunnel users if different tunnels are regulated differently. This could result in challenges when communicating how to use shelters. Tunnel users might look for shelters in tunnels that have no emergency exits or evacuation shelters causing extremely dangerous situations.	**Hyp. 14:** A study should determine how a regulatory revision allowing for the implementation of evacuation shelters should be formulated. This study should consider setting strict requirements for tunnels being considered (traffic volume, tunnel length, capability of local emergency services, etc.).

Terminology	
The term “tilfluktsrom” has some negative connotations due to the current geopolitical situation. It might also cause confusion due to *forskrift om tilfluktsrom* and other areas/fields where the term is being used. “Evakueringsrom” is also considered to be suboptimal. The following work related to evacuation shelters is not bound by the terminology used in the directive. It is possible to use other terms for evacuation shelters if it is deemed beneficial. “Beskyttelsesrom” might be a good alternative term.	**Hyp. 15:** It is necessary to establish a common terminology, and the Norwegian term "tilfluktsrom" (refuge room), which is currently used in the regulation, is not very descriptive and has unfortunate connotations. It is necessary to establish an understanding of which term is the most descriptive and at the same time is in line with the terminology used in the directive.
Regulations relating to the evacuation shelter (and the surrounding system)	
Requirements relating to the design and equipping of the evacuation shelter should be formulated (e.g., in N500). The requirements should reflect a holistic approach, considering how the shelters are expected to be used, the more extensive tunnel system and the systems surrounding the physical tunnel, such as location, capability of local fire departments etc. Certain aspects could be regulated in detail, but in general functional requirements are considered beneficial. Spacing between shelter, capacity and the time people can stay in the shelters has to be considered in a holistic perspective, but minimum requirements could be considered. Relevant themes/topics that should be further considered when putting forth requirements could be: - The time people can safely stay in the shelters - Spacing between shelters - Fire resistance - Water and frost protection - Requirements regarding sectioning - Dimensioning. Evacuation shelters will result in new requirements relating to necessary resources at the TCC, their training and cooperation as well as how they gather and share information. Situations get more complex and more difficult to handle when people evacuate to shelters. For instance, the TCC operator will have to communicate directly to tunnel users inside these shelters, possibly over longer periods.	**Hyp. 16:** It is necessary to determine how the design and functionality of evacuation shelters (along with surrounding system) should be regulated. The scope of this work should consider whether it is appropriate to establish minimum requirements such as spacing between shelters, fire resistance, capacity, etc.

Other relevant regulations	
It is important to be aware of the possible implications, limitations and/or commitments related to adjacent regulations when considering revising existing regulation concerning the ban on evacuation shelters. For instance, the term “tilfluktsrom” could cause issues due to *forskrift om tilfluktsrom*. *Brann og eksplosjonsvernloven* and associated regulations are peripheral regarding tunnels. It should be considered whether the tunnel regulations should be better aligned with fire protection legislation. - *Forskrift om brannforebygging* puts forth requirements as to how fire departments are responsible for inspection objects/constructions that represents high risk regarding fires. - *Forskrift om organisering av brannvesen* puts forth requirements meant to ensure the safety of fire constables. It is important that evacuation shelters do not infringe upon the safety of fire service personnel. - *Storulykkeforskriften* and other regulations related to hazardous materials could mean that it is necessary to cooperate with the Directorate for civil protection and emergency planning when considering the transportation of hazardous materials through tunnels.	**Hyp. 17:** It is necessary to establish a broader understanding as to how other legislation affects or is affected by the establishment of evacuation shelters in tunnels.

5.2 Designing evacuation shelters

Design	
Is there a need to install containers into the niches used as evacuation shelters or is it sufficient to build shelters with exposed rock along ceiling and walls? By using containers, it is considered easier to control the indoor climate, for instance, oxygen levels and necessary oxygen supply.	**Hyp. 1:** It is necessary to study the differences between evacuation shelters based on containers and shelters established with exposed rock on walls and ceilings in terms of safety. The study should include factors such as fire dynamics, fire safety engineering solutions and perceived safety by the tunnel users. The latter would be a continuation of the VR-study performed by Sintef.
As of today, there are no clear requirements concerning the distance between evacuation shelters. The two pilot projects deviate from recommended distance of 250 m, as put forth by Sintef's study. The spacing between shelters are of great importance, for instance due to the walking speed of people walking in/through smoke. The speed can be as low as 20 cm/s. The implementation of directional lighting on the same side of the tunnel as the evacuation shelters as well as speakers or Evacsound could allow for considering spacing between shelters above 250.	**Hyp. 2:** It is necessary to conduct a study focusing on how the distance between cross-passages and evacuation shelters affects the evacuation process. How does distance affect decision-making processes, uncertainty, walking speed, etc.? As part of this study, it should be assessed what measures may be necessary to ensure the safety of tunnel users if the spacing between shelters exceeds 250 m, as well as factors that suggest spacing shorter than 250 m.
Technical installations listed below, inside the evacuation shelters, are assumed to make tunnel users more comfortable using the shelters. Several of the installations mentioned have been identified through previous studies. - Blue lighting in ceiling that gives the impression that the shelter being larger than it is. - Direct phone line to the TCC along with an information board (instructing people how to operate oxygen supply system etc.). - Wi-Fi access allowing tunnel users to connect with friends and family during an emergency.	**Hyp. 3:** It is necessary to determine what installations should be required installed in evacuation shelters and what is preferable. The results must be based on scientific work.
Light fixtures installed above the entrance door of the evacuation shelters should indicate to personnel inside tunnel whether the shelters are being used. This will allow fire fighters to evacuate tunnel users more efficiently. Further, alternative use of the evacuation shelters should be studied. For instance, could the shelters be used by the fire department for storing oxygen tanks used during firefighting? Fire departments could also use the shelters for intermediate "storing" of tunnel users that require assisted evacuation.	**Hyp. 4:** It is necessary to involve fire departments in designing and determining how evacuation shelters should be used. This should also include considering alternative uses of the shelters other than protecting tunnel users who does not exit the tunnel unassisted.

Technical solutions	
To ensure the safety of tunnel users in a better way it is necessary to apply a system perspective. This means assessing the safety as a property of the tunnel system rather than the sum of all safety related measures. Such a perspective will include regulating transportation of hazardous materials, frequency of buses filled with passengers, available external emergency preparedness resources etc.	**Hyp. 5:** It is necessary to consider the benefits and challenges related to adopting a system perspective when performing risk assessments and emergency preparedness analyses for tunnels.
Today the minimum required safety equipment/installations (tunnel class) in a Norwegian tunnel are determined by the length and traffic volume of the tunnel. Tunnel class should instead be determined on the basis of a risk assessment. This would allow for assessing whether dimensioning ventilation system for a 50 MW fire is sufficient, or if it should be dimensioned for a 200 WM fire. It is possible that looking towards the oil and gas industry would be beneficial when deciding upon dimensioning scenarios in a tunnel. Here, minimum requirements related to lighting, water and ventilation forms the basis of the safety installations while there is a requirement to upscale this according to dimensioning scenarios. Hence, it is considered reasonable to establish minimum requirements that are upscaled in order to comply with a performance-based regulation.	**Hyp. 6:** A stronger argumentation is needed regarding how emergency preparedness is being addressed. Can standardized solution and the unique characteristics of the tunnel be considered?
Responsibility	
Does the self-rescue principle mean dimensioning for a worst-case scenario? Who is responsible if tunnel users die inside the evacuation shelter? What responsibility would the tunnel owner have? Or what responsibility does a bus driver have if he directs his passengers into an evacuation shelter, and the passengers dies? Heavy good vehicle drivers, bus drivers and rescue services should practice using the shelters on a regular basis.	**Hyp. 7:** It is necessary to study how the self-rescue principle is impacted when tunnel users seek refuge in evacuation shelters during an incident in the tunnel.

5.3 Operating and maintaining evacuation shelters

Operations and maintenance	
To effectively identify maintenance and repair needs regarding the evacuation shelters, a balance between remote monitoring and physical inspections/surveillance needs to be found. It is considered beneficial to standardize the design and equipment of the evacuation shelters, allowing for a standardized maintenance program. This eliminates the need for separate maintenance programs and instructions for different tunnels or different evacuation shelters within the same tunnel. However, such standardization must still allow for the tunnel's risks, due to its uniqueness, to be considered and be a guiding factor for the final design and equipment of the shelters. There are currently no guidelines for the operation and maintenance of evacuation shelters in Trygg Tunnel. When using evacuation shelters, new equipment is introduced into the tunnel that is not currently covered by existing maintenance programs (such as oxygen tanks and possibly sanitary facilities). Does this require additional personnel to conduct inspections/surveillance, or would it be more effective to train existing personnel?	**Hyp. 1**: It is necessary to determine to what degree the layout and equipment of the shelters should be standardized (both within one tunnel and between different tunnels) in order to standardize maintenance-related tasks. The standardization of the shelters should still take into account that the possibility to designed them in accordance with local characteristics should be ensured.
It is necessary to determine the consequences of maintenance-related closing of evacuation shelters. Will it be necessary to close the entire tunnel due to a closed evacuation shelter? Should other traffic-related measures be put in place? The emergency plan must include the events and conditions that require risk-reducing/mitigating measures.	**Hyp. 2**: It is necessary to determine how malfunctioning or closed evacuation shelters should affect the operations of the tunnel. The findings should be included in guidelines considering emergence preparedness plans for the tunnels.
During the workshop, it was discussed that excessive supervision and inspection can lead to more errors. This can result in a greater need for ensuring competent personnel carry out this work. It was also mentioned that TCC operators can cause unintended malfunctioning (for example, by leaving oxygen valves open).	
During the workshop, it was considered appropriate to limit systems that may cause errors. This will help reduce the need for maintenance and simplify the operation of the shelters. The use of technology in the rooms must also take into account possible future developments, where "today's" equipment may be insufficient compared to equipment available in 10-15 years. Changes in technical equipment can pose challenges related to current operating contracts for the shelters.	**Hyp. 3**: It is necessary to determine how simple or complex systems related to the evacuation shelters that is considered acceptable. Too simple systems will not be able to provide necessary assistance/information etc. during accidents, whereas to complex systems could prove difficult to maintain and operate.
Describing which errors related to the evacuation shelters that require immediate correction must be established and communicated to contractors. Such a system already exists for other systems found in tunnels.	**Hyp. 4**: It is necessary to establish a list of errors related to the evacuation shelters that requires specific actions.

Tunnel users should be trained on the use of evacuation shelters. This could be part of the driver's education program, youths could be invited to inspect the shelters etc. It is also possible that giving locals direct information would be effective, especially if the tunnel is mainly used by locals (as for the Flekkerøy tunnel). Other relevant actors could be truck drivers and bus drivers.	**Hyp. 5**: It is necessary to determine what information/training tunnel users need in order for them to be able to use the evacuation shelters effectively and safely. Part of this work should include determining measures to ensure that tunnel users receive this information/training.

5.4 Control and restriction measures

Controlling and restricting traffic	
The interaction between infrastructure, external emergency preparedness, and usage of the tunnel is crucial to ensuring safety. Limitations in any of these elements can affect the overall safety of the tunnel system. If there are restrictions on usage, there may be fewer potential scenarios that could occur in the tunnel, which could reduce the need for infrastructure and emergency preparedness. It is therefore of interest to study what a reasonable level of flexibility would be regarding controlling and restricting the three aforementioned elements. - Should we allow for more restrictions related to Norwegian road tunnels? - What type of restrictions would affect the safety of the tunnel system?	**Hyp. 1**: It is a need to establish more knowledge related to the benefits and challenges related to increased control and restriction measures of Norwegian road tunnel systems. The study should consider what type of restrictions could be relevant.
What level of control and restriction will society accept? Will increased cost, wait time, longer diversions etc. be accepted by tunnel users / society? It is expected that society, in a broad sense, will not accept too many additional restrictions compared to those implemented today. Hence, it would be necessary to unambiguously highlight the benefits of further, or additional, control and restrictions in a clear way. For instance, benefits such as increased tunnel safety, better traffic flow etc. One should also consider the possibility of implementing different types of measures regarding controlling and restricting traffic depending on what type of tunnel system is being considered. Should one differentiate between rural and urban tunnels? Tunnels with high or low traffic volume? Tunnels where there are possibilities to divert traffic along different roads? What prerequisites must be in place to implement measures increasing control and restrictions related to a tunnel system?	**Hyp. 2**: It is necessary to determine how society will react to further control and restriction measures. At what cost are tunnel users and society no longer willing to accept limitation regarding the use of tunnels?

Incident management	
What challenges and possible solutions exist for when an incident occurs? How does one determine the right course of action for the situation that arises, and how does one ensure good decision support for rapidly evolving situations? How does one control og steer tunnel users during an incident, e.g., through communication? Who will be responsible if communication with tunnel users directly causes hazardous situations, or even fatalities? It is considered necessary to find a balance between controlling a situation and potentially making it worse.	**Hyp. 3**: It is necessary to study what measures are needed to ensure that decision-makers have access to necessary information and can make correct decisions based on this information to act in an efficient manner during an accident. The scope of the work should also include factors or measures that can negatively affect the decision-making process.
What functions are necessary to maintain during an incident to ensure a safe and reliable safety concept where evacuation shelters constitute one of several elements? Are there examples of safety systems to maintains these elements?	
Dangerous goods transport	
It is considered impossible to eliminate the transportation of dangerous goods through road tunnels. Even though the consequence of incidents involving dangerous goods can be catastrophic there are few reported incidents. There are, however, a few tunnels with restrictions or control measures in place regarding the transport of dangerous goods: Hvalertunnelen, in the Ålesund tunnel and the Oslofjord tunnel. Are these examples of permanent measures, or should they be considered temporary until more permanent solutions are implemented?	**Hyp. 4**: It is necessary to study if it is beneficial to implement measures regulating the transportation of dangerous goods through tunnels. The study should regard characteristics relating to the tunnel system that speaks in favor of stricter control and restriction measures.
During an incident	
What measures are required to ensure control during an incident? - Early detection: TCC needs to be notified that an incident has occurred in the tunnel. They need video footage of the accident scene. - Early warning: a system should warn tunnel users about the incident. - Communication: what information is important to share with tunnel users? How should this information be relayed to the tunnel users? - Continuous evacuation lighting leading to safety.	**Hyp. 5**: It is necessary to study how a multitude of safety elements contribute to a safe system in a tunnel. Which of these are more critical than others? Are there room for improving existing elements?

6 Evacuation Shelters – Introductory Considerations of Geotechnical Issues and Proposal of Alternative Methods for Evacuation

The following is a geotechnical note produced by Multiconsult's geotechnical engineer Svein Magnus Halsne.

Evacuation shelters in niches or short tunnel stubs are, from a civil engineering and geotechnical perspective, made by well-known technologies and procedures. A somewhat flexible placement of these niches will be advisable to avoid weak rock formations or zones of water intrusions.

We have discussed three methods for alternative escape routes in new or existing tunnels. All these options can be good options and cost effective in different situations (for example geology, gradient, curvature, ground conditions in the tunnel start points, etc.). The corridor option has not been evaluated in comparison to the other methods in this note because we regard the main issues and costs to be the building of the firesafe corridor.

From both technical and economical side, we consider use of rise drilling and mini TBMs (tunnel boring machines) to be the most effective methods to make parallel tunnels for alternative escape routes. The drilling of small tunnels is cost effective, environmentally friendly and can be executed with little disturbance to the stability of the main tunnel. The tunnel walls are smooth and can require very little support. Raise drilling is generally considered the less costly method and it is also flexible and can be done in sections along the main tunnel which reduces the costs and can be done to avoid weak rock masses and water problems and to reduce the total length of the escape tunnel. For drilling a tunnel in advance of the main tunnel TBM is in the most cases considered the be the best option.

For further works of alternative fire escape methods discussed in chapter 3, we recommend further analyses of the cost compiled with the other relevant costs like constructions, traffic handling, rock support etc. We recommend that the analyses include considerations of the sustainability and environmental impact of the different methods.

In the planning of new single tube tunnels, we recommend considering drilling a small diameter tunnel next to the coming planned tunnel. This tunnel will act as an exploratory adit drive ahead of the advancing main tunnel. This tunnel will give useful information on the geological conditions as well as acting as an escape tunnel during building and operation of the main tunnel. A small TBM tunnel is likely to be the best and most cost effective.

6.1 Introduction

Evacuation shelters in road tunnels are generally not built in Norway due the prohibition in EU directive 2004/54/EC. The result is that the many single tube tunnels in Norway remain without evacuation shelters or alternative evacuation possibilities. The question of evacuation shelters are therefore being investigated in the KATS (kapasitetsløft tunnelsikkerhet) - project.

This note is written as an introductory evaluation of the geological and tunnel constructability perspective when considering evacuation shelters in single tube tunnels.

6.1.1 Scope of Works

This note is an introductory evaluation to the evacuation shelter discussion from a geotechnical and tunnel construction perspective. The purpose of this note is two-fold:

- To give a brief evaluation of some geological aspects related to the construction of evacuation shelters. What are the geological/geotechnical issues that arises when planning such structures?
- To propose cost effective alternatives to evacuation shelters and two tube tunnels. Relevant issues for the proposed methods will be discussed, including technological limitations, feasibility, cost, uncertainties, etc.

The construction of full scale evacuation tunnels parallel to the single tube tunnel, either made with TBM (tunnel boring machines) or drill & blast are well known possibilities, but costly, and are therefore not further discussed in this note.

In this note, the discussion is focused on fire safety improvement of existing tunnels, but the same methods can be applied in the construction of new tunnels.

6.2 Evacuation Shelters- Geotechnical Considerations

6.2.1 General

The evacuation shelters are placed in niches or short tunnel stubs placed at regular intervals along the tunnel, as illustrated in Figure 6-1. The evacuation shelters are built either as installment of pre-made containers, built-in rooms, or using the entire niche/stub as a shelter (as a cavern) with a concrete wall and doors separating the shelters from the main tunnel.

The construction of such local enlargements of the tunnel or short tunnel stubs is fairly simple and well known. Excavation is performed by traditional drill & blast methodology. In tunnels equipped with tunnel lining, such as precast concrete lining or PE-waterproofing lining, this must be removed before excavation. In tunnels where the lining is load bearing the liner should not be removed, meaning that establishing niches can be difficult or not feasible.

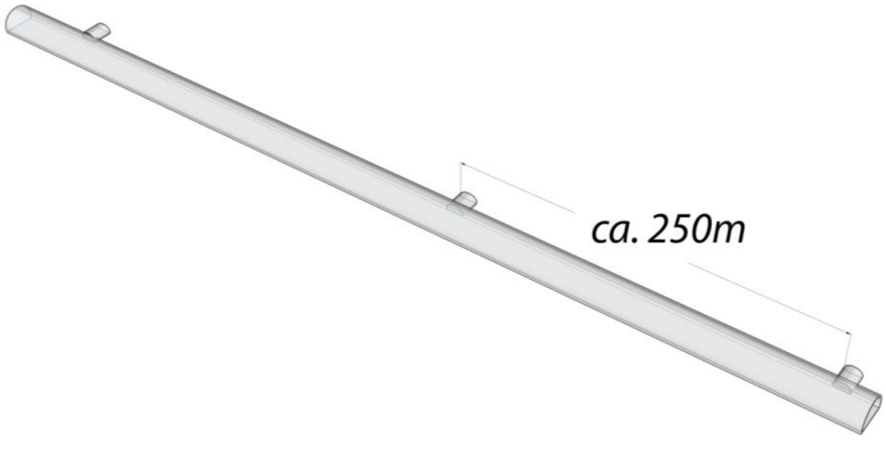

Figure 6-1 Illustration of main tunnel with small tunnel stubs or niches for placement of evacuation shelters.

6.2.2 Geology

In mainland Norway, the rock mass is generally competent providing good tunnel stability. The main exception typically being discrete zones of weakness, i.e., weakness zones, causing stability issues. These zones are typically limited in width, varying from a few meters to tens of meters. Usually, it is only in such zones that heavy support in the form of cast-in-place concrete liners or shotcrete arches are used as a load bearing support element in the tunnel. Norwegian fjords are usually corresponding with regional zones of weakness. Subsea tunnels crossing the fjords have therefore often crossed major zones of severely weakened rock mass.

Some tunnels are made with restrictions of water leakage into the tunnel, either due to environmental concerns or to limit the need for drainage and pumping. The water tightening of tunnels is mainly done by pre-grouting (injection of cement in the rock mass surrounding the tunnel). If the tunnel is constructed in an area where water leakage is prohibited, and pre-grouting has been performed, the excavation of niches can penetrate the injected zone around the tunnel. Water bearing joints can also be an issue with regards to placement of niches, especially in subsea tunnels.

6.2.3 Recommendations

For the above-mentioned issues, to prepare for cost effective and safe construction of niches or short tunnel stubs, it is advisable to be somewhat flexible with regards to the exact placement of niches. Often, geological conditions can vary greatly over short distances due to the above-mentioned zones of weakness. Information on geology can often be found in as-built documentation from the constructional period but can also be mapped by geologists at site. The planning of the niches must consider the location-specific geology and stability of the tunnel. Geological competence should be included in the exact placement of the niches and at site during construction.

Whether the pre-made containers or cavern-type shelter is chosen, the works of construction, stabilizing measures and handling of leakage water is expected to be similar. In both cases, rock bolts and shotcrete are installed as standard procedure dictates. It is likely that the need for water leakage-/drip prevention is smaller in the pre-made container type of shelter. Otherwise, in a geological or tunnel construction perspective neither type is preferable over the other.

6.3 Proposal of Alternative Measures of Evacuation

As of today, the main method for evacuation in Norwegian tunnels is through the portals in single-tube tunnels, and through cross-passages to a parallel tunnel in twin-tube tunnels. An alternative for single-tube tunnels is evacuation shelters placed at regular distances from each other through the tunnel, as discussed in chapter 2. In this chapter we discuss alternatives to these two methods.

We have identified the following methods:

- Parallell small-diameter tunnel
- Connected evacuation shelters (drill & blast or raise drilled)
- Corridor in the main tunnel or in a through-going enlargement of the of the exisitng tunnel

6.3.1 Parallel Small Tunnel

The parallel small tunnel is a small tunnel which main purpose is as an escape route, as shown in Figure 6-2. A drilled tunnel can represent a cost-effective alternative to conventional tunneling by drill & blast. In practice, the equipment needed for excavation of drill & blast tunnels are such that the cost optimal size is from 20-25 m^2. There has been considerable technological development in hard rock drilling of small to medium sized tunnels in recent years, which makes these alternatives more and more effective compared to blasted tunnels.

There are many advantages to drilled tunnels. The small diameter and smooth surface of the tunnel means that there is less need for rock support. The excavation method is mainly electrical driven and there will be less excavated rock volume compared to an equivalent drill & blast tunnel, which means less transport costs and less environmental footprint. Drilling, compared to drill & blast, can be done with minimal effect on stability of the main tunnel and minimal hinderance of the ongoing traffic in main tunnel during construction.

The method is, however, less flexible than drill & blast and favors projects with good rock mass. Both long-hole drilled tunnels and TBMs require a significant area for rigging near the tunnel opening, which furthermore will limit the number of suitable projects.

In new tunnels, it can be advantageous to drill a small diameter tunnel next to the coming planned tunnel, and to let this tunnel act as an exploratory adit drive ahead of the advancing main tunnel. Later, small tunnel stubs to connect the main tunnel with the escape tunnel can be made by drill & blast from the main tunnel to the smaller tunnel.

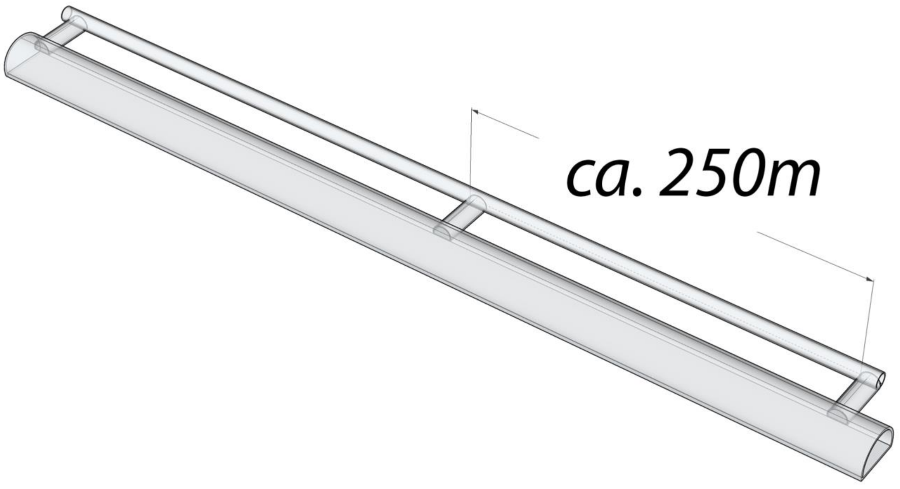

Figure 6-2 Illustration of parallel small tunnel next to the main tunnel connected by short tunnels.

Long-Hole Drilling

Long-hole-drilled tunnels are drilled by a remotely controlled drill head that travels on a long drill rod inside the rock. Today these tunnels can be made up to approximately 1500 mm in diameter and 2-3 km long. Installation of rock support must be done after drilling and is challenging due to the small diameter which does not give necessary space for bolting, shotcrete etc.

The long hole drilling will also have some limitations on curvature and require a minimum slope of at least 4 % to remove the cuttings from the drilling.

Mini TBM

TBMs (tunnel boring machines) drills a circular tunnel and is made in sizes ranging from man-height up to more than 10 meters. Unlike the long hole rotation drilling, the operators work inside the open TBM while drilling. It is therefore possible to do light rock support during drilling. The operation is entirely run on electricity. The smallest diameter TBMs (Ø 1,9-2,5 m) have become cost-wise very competitive compared to traditional minimum size drill & blast tunnels. The TBMs are considerably faster than drill & blast but can have a longer timeframe for mobilization and preparation of the site.

Raise Drilling

The parallel tunnel can be made by raise drilling. Raise drilling is performed by the drilling of a pilot hole of smaller diameter which is then expanded to the required final diameter by a larger reamer head. The method will require enlarged niches to make room for the equipment needed for the drilling. A niche with floorspace of at least 100 m^2 m will be necessary and sufficient height for lifting equipment.

6.3.2 Connected Evacuation Shelters

Connecting two-and two evacuation shelters by an escape tunnel can be a viable option to the full-length parallel tunnel. The escape tunnels between the shorter tunnel stubs with shelters can be excavated by drill & blast or by horizontal raise drilling. An example of this layout is presented in Figure 6-3.

The main advantage of the method is obvious, only 50 % excavation length is accomplished compared to full length tunnels, and isolated shelters are avoided. Compared to a full-length tunnel however, as the evacuation shelters are sealed off from the main tunnel, access to the escape tunnel is limited.

The construction of the niches must be excavated by conventional drill & blast. The escape tunnels can be excavated by drill & blast, or by raise drilling, as described in chapter 3.1.3

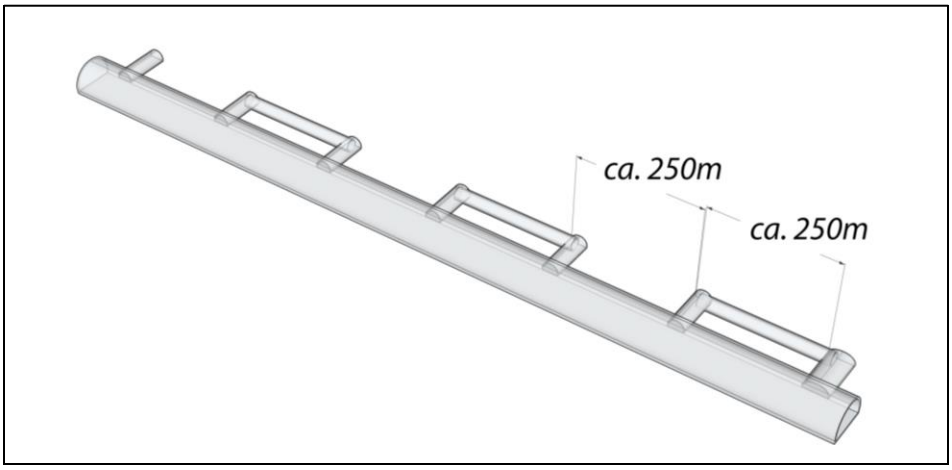

Figure 6-3 Illustration showing a system of short escape tunnels connecting shelters

An advantage with the method is that placement of the niches and tunnel can be chosen to avoid weak rock and water intrusions.

Horizontal raise drilling is possible, but a slope of >3⁰ is preferable for effective removal/flushing of the drill cuttings.

6.3.3 Corridor in the Main Tunnel or in a Blasted Extension of the Tunnel

The possibility of creating an escape corridor along the side of the main tunnel could be a viable alternative. For most tunnels this will require blasting an extension on one side of the tunnel, as shown in Figure 6-4.

Expanding the tunnel span by blasting is a fairly well known and used practice in Norwegian tunnels, mainly to widen the road and to better the line of sight in the tunnels. A large part of the existing rock support in the tunnel must be replaced during the construction. In most tunnels with good rock conditions the technical execution of this is feasible. In tunnels or part of tunnels where the rock support consists of concrete lining or shotcrete ribs, the method can be highly demanding and costly or entirely unfeasible. In any case the expansion of the tunnel demands extensive works in the main tunnel lane, causing issues with the ongoing traffic flow.

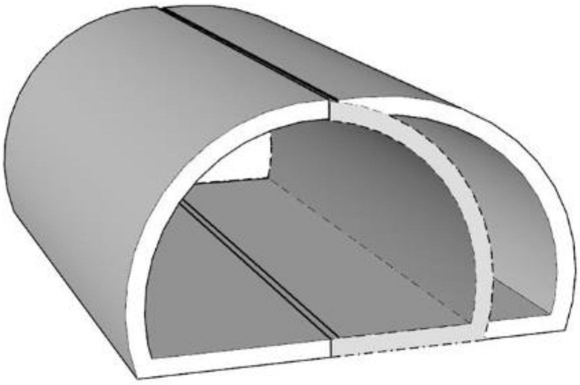

Figure 6-4 Illustration of an extension of the main tunnel by blasting.

6.4 Cost Evaluation

The cost estimate for the different alternatives is complex and the excavation cost is just one part of the total cost. For the estimations we have used costs in projects Multiconsult are involved and also received input from contractors.

In our experience excavation cost of a blasted tunnel of minimum cross section (20-25 m^2) are about NOK ca. 30-40 000,- per meter tunnel. The excavation cost of a ca. 3 m^2 (2 m diameter) tunnel made by TBM is estimated to NOK ca. 20-25 000,- per meter tunnel. Because of the higher start cost of the TBM method, the tunnel length should be more than 1-2 km for the cost to be in this range. Raise drilling of about 1,5-2 m diameter tunnel with raise-drilling can be in the range NOK ca. 15-20 000,- per meter tunnel for a typical 200-300 m long hole. Long hole drilling can be done in the price range of ca. 18–25 000,- per meter for holes longer than approximately 500 m.

The tunneling costs are rough estimates of the cost of excavation based on our experience and do not include planning, site preparations, traffic handling, rock support, disposal of excavated rock etc. The costs will vary greatly based on site specific conditions. The costs that are not included will also vary somewhat between the different methods, but for a cost comparison between different methods of tunneling this cost level can be used.

Of the alternative methods discussed, excavation costs are lowest for the corridor option, where the excavation costs are estimated to less than NOK 5000 per meter tunnel for a 5-10 m^2 extension. The main costs with this option are, however, assumed to be the construction costs of the fire safe corridor itself.

With the exception of the method with a corridor in the main tunnel, raise drilling is the method that has the highest cost saving potential. This method is generally the cheapest.

6.5 Conclusion

Evacuation shelters in niches or short tunnel stubs are from a civil engineering and geotechnical perspective, made by well-known technologies and procedures. A somewhat flexible placement of these niches will be advisable to avoid weak rock formations or zones of water intrusions.

In this note we have discussed three alternative methods to build escape routes in new or existing tunnels. All these options can be good options and cost effective in different situations (with regards to variations in geology, gradient, curvature, ground conditions at tunnel start points, etc.). The corridor option has not been evaluated in comparison to the other methods in this note because we regard the main issues and costs to be the building of the firesafe corridor.

From both technical and economical side, we consider use of raise drilling and mini TBMs to be the most effective methods to make parallel tunnels for alternative escape routes. The drilling of small tunnels is cost effective, environmentally friendly and can be executed with little disturbance to the stability of the main tunnel. The tunnel walls are smooth and can require very little support. Raise drilling is generally considered the less costly method and it is also flexible and can be done in sections along the main tunnel which reduces the costs and can be done to avoid weak rock masses and water problems and to reduce the total length of the escape tunnel. For drilling a tunnel in advance of the main tunnel TBM is in the most cases considered the best option.

For further works of alternative fire escape methods discussed in chapter 3, we recommend further analyses of the cost compiled with the other relevant costs like constructions, traffic handling, rock support etc. We recommend that the analyses include considerations of the sustainability and environmental impact of the different methods.

In the planning of new single tube tunnels, we recommend considering drilling a small diameter tunnel next to the coming planned tunnel. This tunnel will act as an exploratory adit drive ahead of the advancing main tunnel. This tunnel will give useful information on the geological conditions as well as acting as an escape tunnel during building and operation of the main tunnel. A small TBM tunnel is likely to be the best and most cost effective.

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