Firefighting safety and efficiency

In twin-tube city road tunnels

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Preface

This report is a part of the final exam in the Fire engineering program at Lund University. This report is based on interviews with fire department personnel and tunnel managers in Iceland, Sweden, Norway, Finland, and Denmark. I wish to express my sincere gratitude to the interviewees for their participation, interest, and enthusiasm.

I also want to thank my supervisor, Håkan Frantzich, and Böðvar Tómasson, for valuable feedback and reflection during the writing period, and finally, my wife and children, who give me endless support and love.

Abstract

Key question: Can firefighting tactics in twin-tube road traffic tunnels be made safer and more efficient through infrastructure design and installed equipment.

Method: A literature study was conducted, and individuals in the Nordic countries with experience in the field were interviewed. All gathered knowledge was analyzed, and suggestions for solutions were brought forward.

Results: They included how to use different parameters that affect firefighting tactics in the design phase to evaluate if the design provides an opportunity to perform rescue operations - providing valuable insights into the opportunity to increase firefighters safety and efficiency in twin-tube tunnels, with the potential to minimize the consequences in case of emergencies.

Popular science

Efficient traffic flow plays a big role in modern cities. Increasing trend in cities is to move traffic underground to lower noise pollution, use the area above ground for further development and enhance safety for both traffic users and pedestrians.

Even though tunnels can be made safer than open roads, there are possibilities that incidends develope into catastrophic events. While designing road traffic tunnels the safety of users is one of the main focus. When incidents take place, fire departments first responders are called to the scene, by doing so, there is a possibility to minimize the consiquences and steer the emergency development towards a better outcome for people in distress as well as the tunnel owners.

To increase the possibilities for the fire departments to proceed their mission, it is important to include their need and limits in the tunnel design and support them to operate safely and efficency during emergencies. How can firefighters safety and efficency be supported by different design solutions and regulations?

In this report I analyse how tunnels are designed in the Nordic countries, regarding fire fighters safety and efficency, by litterature study and interviews, interviewing personell both related to the design and management side as well as experienced on scene commanders from different fire departments.

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1 Introduction

Transport systems are essential in industrial societies urban, economic, and social development. Utilizing underground space for transport has been a continuing trend across the globe during past decades (Cui & Nelson, 2019). Underground transport systems, such as city tunnels, have been chosen by cities as potential solutions for solving urbanization problems, such as noise and air pollution and traffic congestion, allowing cities with land shortages to expand (Cui & Nelson, 2019; Hoeven, 2011). This suggests that underground infrastructure, such as city tunnels (see figure below for an explanation of how city tunnels can be designed), contributes to sustainable urban development (Sterling and Nelson, 2013). However, city tunnels are not without risks. Tunnels form a large portion of the infrastructure market, and thousands of people and tons of goods pass through them daily (Athanasopoulo et al, 2019, p. 1). Palm et al. (2016) mention that underground structures represent a complex environment with other risks than everyday enclosure fires. Tunnel fire safety is, therefore, a low probability-high consequence risk issue (Gehandler, 2020, p. 31).

The main reason for conducting this study is the construction of new twin-tube tunnels in Reykjavík, Iceland. The tunnel design is supposed to fulfill Icelandic requirements for new tunnel constructions and the Norwegian requirements for tunnels, N500:2022. In those requirements, only few guidelines are provided about rescue services and how to ensure that they can fulfill their task in case of an emergency. The European Union regulations for tunnel structures, states, that safety measures should ensure that emergency services can act effectively (2004/54/EC, 2004), but without further guidelines.

A considerable amount of literature has been published about city tunnels. Previous studies show that the accident rate in road tunnels (excluding portals) is lower than on open roads, but the consequences tend to be more severe (Amundsen & Ranes, 2000; Nussbaumer, 2007). By allowing traffic to flow through tunnels instead of an open road, the negative effect on drivers of sudden weather changes is lowered, distances between pedestrians and vehicles are lengthened, and surveillance cameras can be more efficient due to more constant sight without the effect of rain, sun, snow, and etcetera. A study from Israel shows that redirecting traffic from open roads to tunnels saves travel time, reduces air pollution, and decreases traffic noise in the environment and its surroundings (Ayalon et al., 2016), commonly appreciated by city dwellers.

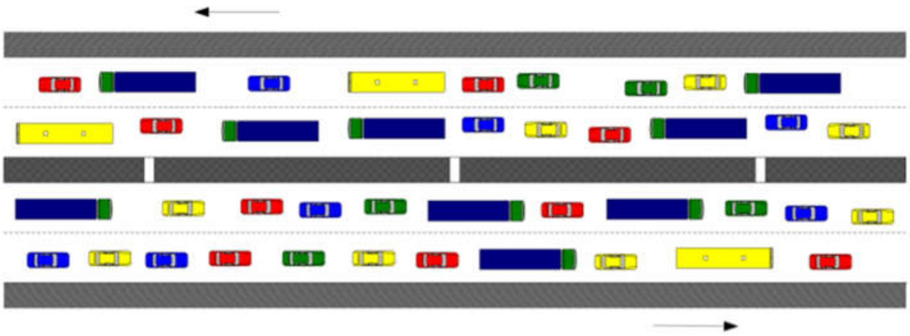

Figure 1: Twin-tube tunnels, with separated traffic flow, one setup for twin-tube tunnels or city tunnels (Ingason et al., 2005).

Many studies can be found regarding tunnel safety. However, fewer are to be found regarding how to support the safety and efficiency of fire departments when responding to emergencies and how to design such infrastructure to support those interventions.

Previous literature has indicated a need to understand various aspects of ensuring the fire departments safety and supporting effective response. This report attempts to add to this knowledge gap.

1.1 Objectives

This report evaluates if and how firefighting operations in twin-tube road traffic tunnels can be made safer and more efficient through infrastructure and equipment design. By doing so, increased safety and efficiency can lead to lowered consequences in case of emergencies in twin-tube tunnels.

To achieve this objective, knowledge of hazards, challenges, firefighting tactics, tunnel management procedures, modern tunnel design, and emergency equipment is gathered through literature study.

The report also includes interviews with experienced firefighters and tunnel management personnel to gather their experience, viewpoints and opinions. By interviewing experienced firefighters, their viewpoints and opinions regarding what hazards, challenges, and tactics are involved during firefighting operations in twin-tube tunnels are brought forward, and how they suggest an improvement. By interviewing experienced personnel within the tunnel management, their viewpoints and opinions regarding how modern design, commonly installed equipment, and procedures support firefighters during their operations are brought forward and how they think it can be improved.

By analysing all gathered knowledge, parameters that affect firefighters safety and efficiency during twin-tube tunnel firefighting operations are identified. By knowing what parameters affect firefighters the most, designers can evaluate them in the early stages of the tunnel design phase and enhance the design and building phase to a more structured track with fewer adjustments and costs in later stages.

The report also discusses how to involve potential firefighting tactics in the design phase and aims to bring forwards suggestions for solutions.

Answers to the following questions where sought:

- What design criterias affect firefighting operations according to previous research and how do they affect the safety and efficiency of firefighters.
- What regulations that affect the safety and efficiency during firefighting operations are in force in the Nordic countries.
- How is modern firefighting response proceeded and how does modern fire safety design function during firefighting operations according to experienced individuals in tunnel incidents.

1.2 Methodology

A literature study was conducted, and individuals in the Nordic countries with experience in the field were interviewed. Using the information from the literature search, an interview guide was structured to ensure the interview questions were relevant and focused on the research goals. Additionally, invitations were sent out to potential participants to recruit individuals for the interviews. Planning and preparation ensured that accepted interviews were conducted smoothly and efficiently. After conducting the interviews, the information collected was compared to the existing literature to identify whether the search needed to be expanded. Finally, all collected knowledge from the literature and interviews was analyzed and solutions for improvements were brought forward (See the methodology flowchart in the figure below).

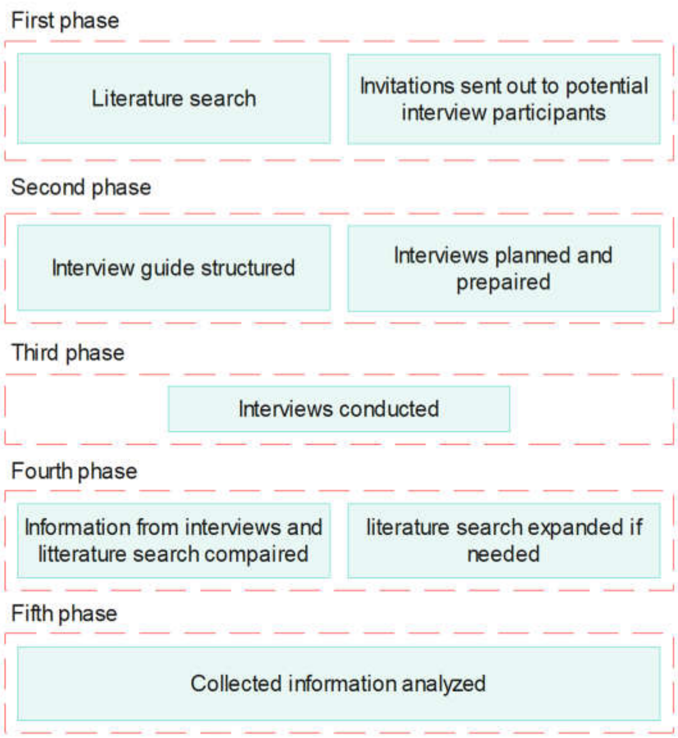

Figure 2: Flowchart of methodology setup

1.3 Limitations

This report is limited to English, Norwegian, and Swedish literature when gathering data. Though information regarding all kinds of tunnels will be of interest, the aim is to provide information related to tunnels located in cities, twin-tube tunnels, with each traffic direction separated.

This report is strictly limited to supporting the safety and efficiency of firefighters during operations in the previously mentioned tunnel. Therefore, it is thought that an incident has already occurred, and rescue operations from the fire department are required. This report does not include other safety measures for tunnel users and dwellers in the surrounding environment.

The report is focused on tunnel design and rescue tactics on the Nordic countries. The decision to exclude countries outside the Nordic from this report is rooted in the need for a focused analysis of tunnel fire safety practices within the Nordic context. It is however important to note that while countries outside the Nordic are not included in this report, their tunnel safety practices and experiences may offer valuable insights for separate studies or comparative analyses involving countries with similar infrastructure and regulatory contexts.

2 Literature review

This chapter introduces results from the literature search related to firefighting in tunnels, modern design measurements, and regulations regarding design in tunnels. Moreover, previous research about regulations in the Nordic countries and previous research regarding tunnels, fire in tunnels, and firefighting in tunnels has been brought forward.

2.1 Search strategy

In the first round, the database of the Lund University Libraries search engine (LUBsearch), which among others, includes ScienceDirect and Scopus databases, was used to find firefighting-related results. After reviewing a few first hits, more efficient keywords were defined. In the second round, selected keywords were used in two databases, the one mentioned above, LUBsearch and DiVA (Digital science archive used by fifty authorities and schools in Sweden). In the third round, public documents from tunnel safety and fire conferences were gathered, and as a secondary source of information, interesting documents were gained during interviews.

The table below shows the defined keywords and the search result hits in the second round, and for the flowchart of the search strategy, see the figure below.

Table 1: Search result hits for chosen keywords in two different search engines.

Key search word	LUB Search	DiVA
Tunnel	376607	555
Tunnel AND Safety	19853	101
Tunnel AND Fire	7734	89
Tunnel AND Rescue	1742	25
Tunnel AND Safety AND Rescue	426	38
Tunnel AND Firefighting	256	5
Tunnel AND Safety AND Firefighting	138	4

The databases publications were refined by their title, abstracts, and results in the fourth and last rounds. Excluded publications were those in languages other than Norwegian, Swedish, or English. Finally, refined literature and related regulations in the Nordic countries were reviewed. The following subsections present relevant literature and regulations in the Nordic countries regarding how to support safer and more efficient firefighting operations.

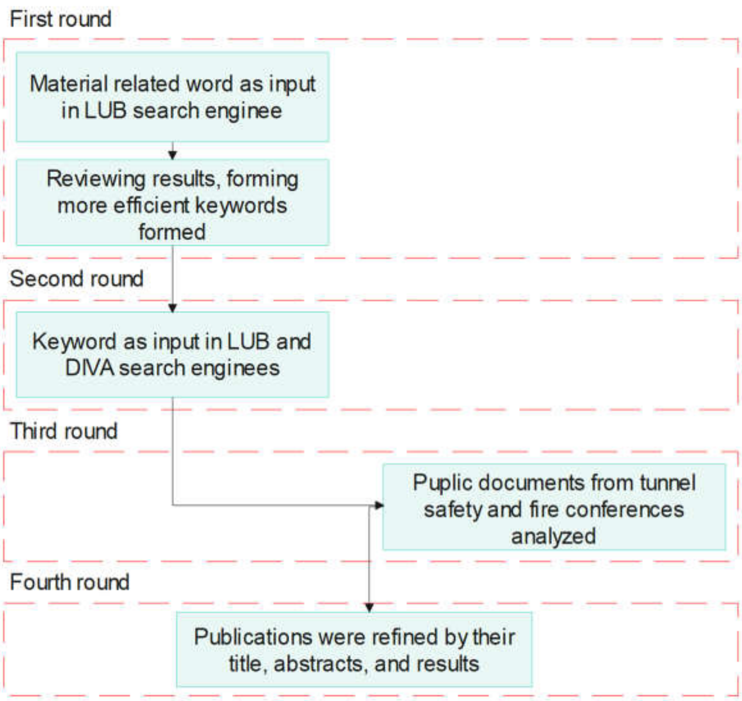

Figure 3: Flowchart showing the procedure of literature search.

2.2 Firefighting operations

The following section gives an overview of research about the involvement of firefighting in tunnels, the need for information, equipment, or infrastructure, and how to support a safer environment and efficiency for firefighters. Sardqvist (1996) stated that to make a good decision; one must have good information on which to base the decision. In an analysis of underground firefighting tactics, Palm (2014) research relates to making an effective decision on the scene. According to Palm, incident type is decisive for interpreting the scene. Therefore, the operation commanders must get as accurate a description of the scene as possible to allocate the right resources and make the right decision regarding rescue efforts. The seriousness of the fire or accident can be both overestimated and underestimated due to inaccurate information; he mentions that underestimation of the scene is the most serious, as resource building and risk assessment may be missing and underestimated due to lack of or incorrect information. To conclude, Palm also mentions the importance of knowledge regarding the resource capability to speculate the rescue effort accurately (2014). Successful engagement with fire in tunnels is not only related to informed decisions but technical ones as well. For the fire department, the most effective consequence-reducing factors are that there are short and straightforward evacuation routes, that the firefighters can, in a short time, get to the source of the fire, and that the fire development has not gotten too large before the firefighting begins. These different prerequisites can be achieved in different ways, but there must be an overall safety assessment where all involved parameters are identified and all made to work together; by designing in that way, there can be creation of a high level of safety in the tunnels (Ingason et al., 2005).

Gehandler (2020) wrote that to provide means and safety for rescue operations, the main requirement is that the rescue service can undertake life-saving and fire-extinguishing activities with satisfactory safety for their personnel. A rescue plan must be drawn up with the local rescue service. Furthermore, it must be possible to locate the position of the fire and reach the fire, to have means for controlling the smoke and extinguishment, and to be able to communicate by radio in the tunnel. To ensure the safety of rescue personnel, Gehandler (2020) states that several measures can be taken: a ventilation system that can control the heat and smoke, fixed firefighting systems (FFFS) can reduce the fire size and cool down the fire and surrounding structure, and the load-bearing capacity should be structured to their need. This requirement can be verified and developed through scenario exercises, training, or other means (Gehandler, 2020). Ingason et al. (2005) mentioned in their rapport that the fire development in tunnels significantly impacts the fire departments possibilities to perform effective operations. When firefighting in tunnels, one should be adapted to handle fires of the size that may be relevant to fight. According to Ingason et al. (2005), the three criteria likely to affect firefighting operation dimensioning in tunnels will be:

1. How many evacuees must be supported toward a safe exit?

2. How large is the fire and, therefore, how high temperatures and heat flux affect the firefighters

3. How long distance will firefighters have to move in a smoke-filled environment?

According to Kim et al. (2010), when analysing effective firefighting operations in road tunnels, selected strategies and decisions regarding what access points should be used and how the ventilation should be controlled are crucial for the outcome of any attack. Gehandler (2020, p. 52) also mentioned similarly in his doctoral thesis that to enable efficient firefighting and rescue in tunnels, the fire department must be able to locate the source of the fire, have some ability to control the smoke, and be able to communicate via radio inside the tunnel. These factors can be supported by including ventilation systems to retain heat and smoke, integrating fixed firefighting systems to reduce the fire size, cooling the fire and surrounding structure, and designing the load-bearing capacity concerning possible reasonable fire scenarios supported.

Palm et al. research of underground firefighting tactics, Palm (2014) noted that the most significant delay of time between the beginning of operations with breathing apparatus (BA) and the start of extinguishing was building up the hose system, for example, moving hoses, connecting couplings, and filling them up with pressurized water. Palm (2014) suggested reducing that time by simplifying the hose system and having the hose systems sections ready and coupled. As demonstrated, simplifying procedures in firefighting could reduce the risk and ensure an effective fire rescue capability. In order to enhance fire rescue capability in tunnels, Gehandler (2020) mentioned that scenario exercises or other activities are of good use when preparing for fire in tunnels. During Palm et al. (2016) tests of firefighting in tunnels, he stated that in those tests, it would have been impossible without an infrared image camera.

2.2.1 Firefighting strategies

"The key information for determining the outcome of any operation is what types of an incident is happening in the tunnel and how fast the first unit on the scene can approach within the attackable area and start firefighting" (Kim et al., 2010). Tunnel fires differ from building compartment fires in at least three important ways: firstly, the effects of the ventilator factor, secondly, the flashover conditions and thirtly, the stratification development is referd to as three important terms (Ingason et al., 2015). As mentioned above in this section, obtaining information regarding the scene is of the essence; it will need to be done rapidly and is usually done by the incident commander of the first arriving unit (Kim et al., 2010). Needed information in the first phase of operations is listed in the same report as; what type of fire, number and types of vehicles involved in the original fire, the existence of trapped people, and the location of the fire. "The top priority should be rescue operations rather than any other work of the fire brigade." (Kim et al., 2010)

For each scenario, a strategic plan is dependent on the fire development; if the fire development is thought to have exceeded the capabilities of the first unit arriving, the strategy should be too defensive (for an explanation of how possible scenario could be, involving a burning bus, location of firefighting units and their entries, see next two figures below).

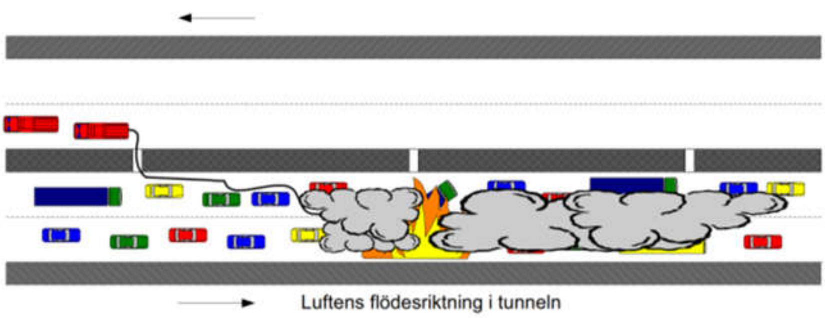

Figure 4: Possible scenario setup when one firefighting unit has arrived, arrows indicate the airflow in each tube (Ingason et al., 2005).

In a report about rescue operations in road tunnels by Ingason et al. (2005), a theoretical scenario for a fire in a bus (2 – 25 MW) was analysed; according to their calculations, one standard hose nozzle is not enough, and a second BA-team is needed for support.

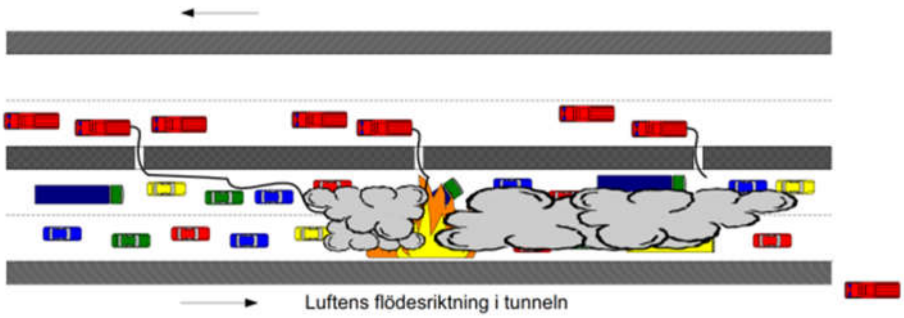

Figure 5: Possible scenario when more resources have arrived, arrows indicate the airflow in each tube (Ingason et al., 2005).

Meaning that the first unit arriving would try to minimize the fire spread until further resources arrive. If the fire development has not exceeded the first units capabilities, it is better to choose an offensive strategy to approach the fire source for effective control (Kim et al., 2010). In the same report, Kim et al. described typical examples of operational procedures for the defense approach:

1. The first access is made from the unaffected tunnel tube or from the upstream side of the tunnel.
2. Search and rescue operation are conducted on the upstream side of the fire.
3. The fire brigades on the downstream side position themselves in a safe location and help the escaping people out of the tunnels or stop the fire spread if it is necessary and possible. They should have a good knowledge on the fire spread and flame length because flame length can be as long as 60-100 m in a short time after the ignition which might put firefighters in danger as well as escaping people.
4. The later arriving teams help the first arriving teams with search and rescue operations or protect the rescuers from the heat and smoke.
5. After the upstream side of the tunnel has been cleared of trapped people and vehicles, the direction of air flow is reversed so that search and rescue can be made on the original downstream side.
6. During the search and rescue on the original downstream side, fire brigades on the opposite sides of the tunnels retreat to safe places and prevent fire spread.
7. Once the fire decreases is enough to be tackled by fire brigades, change of strategy into an offensive one is initiated.
8. When trapped people are confirmed regardless of their locations, saving them is the top priority over any other operation above. (Kim et al., 2010)

Some new tactics have been tested for when BA-teams, search and rescue in longer rail tunnels (Storm & Kumm, 2023). These tests have shown increased movement speed and therefore the possibility of increased efficiency for when BA-teams are searching for evacuees in distress and not in the need of moving waterfilled hoses along to protect them from the fire development. These tactics depend on the fact that the distance to the fire source is sufficient long, so that there is no risk of fire development in their environment.

2.2.2 Breathing apparatus

Two different systems are used to allow firefighters to enter an environment with an unhealthy atmosphere. The more frequently used is called self-contained breathing apparatus (SCBA) or breathing apparatus (BA), a system involving tanks with high-pressured air, valves to open for airflow and decrease the pressure toward the firefighters airway, and a mask to allow firefighters to breathe without contaminated air reaching into their airway. The system is an open circuit, allowing used air from the firefighter to flow out of the mask and new air toward the mask. The latter system, used by some fire departments, is oxygen breathing apparatus (OBA), sometimes referred to as a rebreather, it has the same purpose as BA, but instead of an open air circuit, the system has a closed air circuit, absorbing carbon dioxide from used air, adding more oxygen and circulating it towards the firefighters airway again, this system gives firefighters extended working periods in an unhealthy atmosphere (IFSTA, 2013). Firefighters using breathing apparatuses, most commonly two individuals traveling together when entering an environment where unhealthy air can be assumed, will be referred to as BA-teams hereafter.

Kumm et al. (2014) tested different approach technics for BA-teams while entering tunnel under fire, doing that research the air consumption was measured per individuals. The air consumption that was registered in previous mentioned tests was analysed further by Palm et al. (2022), showing that when BA-teams are equipped with two 3 liter air bottles (most common size in the Nordic countries), the maximum safe distance to travell in tunnels is around 75 meters. For longer distances, larger air bottles (commonly used by BA-teams in cold environment including toxic chemicals) are recommended to ensure air during extinguishment and retrieve.

2.3 Management

It is in favor of the tunnel owner, users, dwellers nearby, and emergency responders that all organizations managing tunnels is highly functioning; this becomes more important as the design becomes more complex. This includes daily operations, maintenance, traffic control, and emergency management (Gehandler, 2020).

2.4 Modern design measurements

The following section introduces information regarding tunnel design measurements related to the previously mentioned safety criteria.

2.4.1 Fire development and heat flux

In the early phase of tunnel safety design, one of the first criteria that need to be figured out is the design of fire development. Fire development is the most critical factor in underground facilities and governs the possibilities for the fire department to perform. It also affects the evacuation process, as fast-growing fires can surprise the evacuees on their escape route, which could result in evacuees needing rescue from the fire department. A fast-growing fire and high energy release include heat and smoke gasses, which can delay firefighting (Palm, 2014).

Multiple tests have been performed to analyze possible heat release rates in road tunnel fires, one of them proceeded in the Runehamar tunnel by Ingason and Lönnemark (2004), as one large pool fire and four mock-ups of heavy goods vehicles were tested. As stated in the report, the heat flux towards the ceiling was extremely high, or around 300 – 400 kW/m^2. The heat flux towards the road surface was measured 10 m downstream and got up to 250 kW/m^2. According to Ingason and Lönnemark (2004), most burnable materials ignite when receiving a heat flux of about 20 – 25 kW/m^2. The same study measured the heat flux towards attacking firefighters up and downstream. Ingason and Lönnemark (2004) conclude that in those scenarios, a fire extinguishing attack would have been impossible from downstream the fire for the first 30 – 40 minutes. When the fires were in their peak heat release, an extinguishing attack without some extra heat shields would also have been impossible from upstream, where the heat flux was measured above 5 kW/m^2 (the limit mentioned for BA-teams), 25 m away from the source. For firefighters to be able to extinguish a fire, they have to get the extinguishing material on the fire source; when using standard equipment and regular water at 6 – 8 bars of pressure, the maximum distance is around 20 meters Kumm et al. (2022). Ingason et al. (2005) calculated the distance for 5 kW/m^2 heat flux for different fire developments, including ventilation velocity that prevents back layering (See figure below).

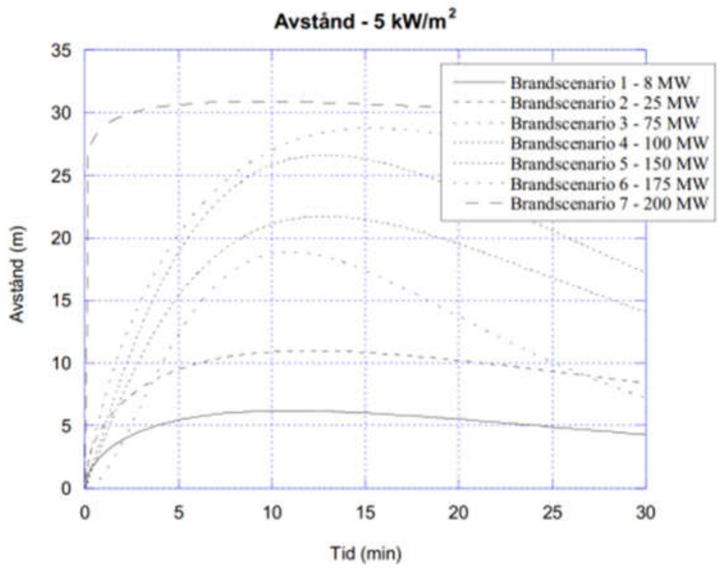

Figure 6: Critical distances regarding maximum heat flux for firefighters (5 kW/m2) (Ingason et al., 2005).

In the book Tunnel Fire Dynamics, Ingason et al. (2015) show in details, possible ways to calculate theoretical values for heat flux and gas temperature as well as other important factors when figuring out possible scenarios in tunnels during fires. The authors also write in detail what factors affect the fire growth and the environment during tunnel fires as well as how tunnel fires differ for more common compartment fires.

2.4.1.1 Concreted spalling

High temperatures can appear in the ceiling of tunnels while under fire. Studies and tests show that the temperature close to the ceiling can reach up to 1350 °C (Yao, 2019, p. 12). It is well-known by professionals in fire safety and firefighting that concrete and steel structures load-bearing capacity lowers in high temperatures. Spalling can appear for concrete experiencing high temperatures, minimizing the isolation towards arming steel, allowing the steel armor temperature raising even quicker, and losing its load-bearing capacity (Connolly, 1995).

Some types of concrete are more prone to spalling from a fire; the probability can be lowered by choosing suitable concrete or thermal insulation towards the possible fire (Gehandler, 2020). Palms (2014) states that spalling is important when deciding different tactics during underground fires; it is a key factor when determining if the fire department should continue its operations or if it must withdraw from its approach.

2.4.2 Detection and surveillance systems

When reading through literature regarding detection and surveillance systems, it becomes evident that fast detection and the availability to analyze the scenario quickly are of the essence. Accurate information as a basis for decisions about the direction of the rescue effort and the choice of work methods is crucial and is especially important for making a risk assessment during the operation. (Bergqvist, 2000). The lack of overview in the event of an accident must be dealt with and resolved. A practical method is to install monitoring equipment in tunnels with a high-quality communication system and a user-friendly interface for the municipal rescue service to use this information as decision support during the operation (Ingason et al., 2005).

In a report by Gehandler et al. (2012, p. 44), it is mentioned as a cheap solution for safety equipment is manual fire detection (alarm buttons) and emergency telephones.

What matters to the emergency dispatch center is to obtain correct information from the callers and share that information as quickly as possible with responding units, to dispatch the right type and number of resources to the right places. This process required, in turn, an informed understanding of what mattered for each of the organizations that would be dispatched to work in the tunnel (Eklund et al., 2022).

Today, automatic surveillance cameras in tunnels can detect multiple abnormalities in their sight, such as congestion, incident detection, loss of visibility smoke, spilled cargo, stopped vehicles, pedestrians, vehicle speed, average vehicle speed, vehicle distance, traffic density, license plate recognition, vehicles driving in the wrong direction and more (*Smart Tunnel Integration*, n.d.).

2.4.3 Ventilation

Providing firefighters with a smoke-free environment raises their safety and efficiency; as their movement speed increases, the time between entry and the fire extinguishing starts decreases, and their endurance increases as heat exposure and breathing air are minimized (Palm, 2014). However, tests have confirmed that more oxygen is also induced into the fire source with ventilation velocity and increases the fire growth rate (Ingason & Lönnermark, 2004).

Most commonly, in twin-tube tunnels, the smoke ventilation is directed in the same flow as the traffic with longitudinal ventilation (see figure below for explanation); by doing so, the evacuees upstream of the fire source can evacuate without being affected by the toxic gasses. Individuals downstream of the fire source should be able to drive out before the smoke catches them. This could, however, not be the case if the fire ignites far back or in the middle of congested tunnels where the moving speed of traffic is lower than the smoke ventilation velocity. A low air velocity and greater tunnel cross-section improve the conditions for evacuees, while more increased velocity increases the rate of growth of the fire, and lower ceiling height brings the smoke layer closer to evacuees. Therefore the goal for twin-tube tunnels with one-way traffic flow in each tube should aim to keep the ventilation velocity at its minimum during evacuation (Ingason et al., 2005).

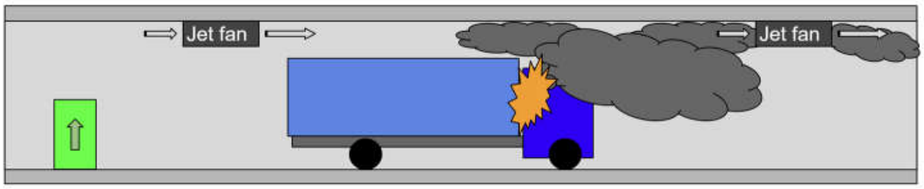

Figure 7: Longitudinal smoke ventilation with jet blowers

Ingason et al. (2005) also described an alternative to prevent the risk of longitudinal ventilation in congested tunnels, including semi-transversal ventilation (see figure below for explanation), which can be used. Semi-transversal ventilation is when smoke extraction points are distributed along the tunnel length to ventilate the smoke gasses. It is vital that when designing this setup, it is dimensioned to handle possible fire development and smoke production.

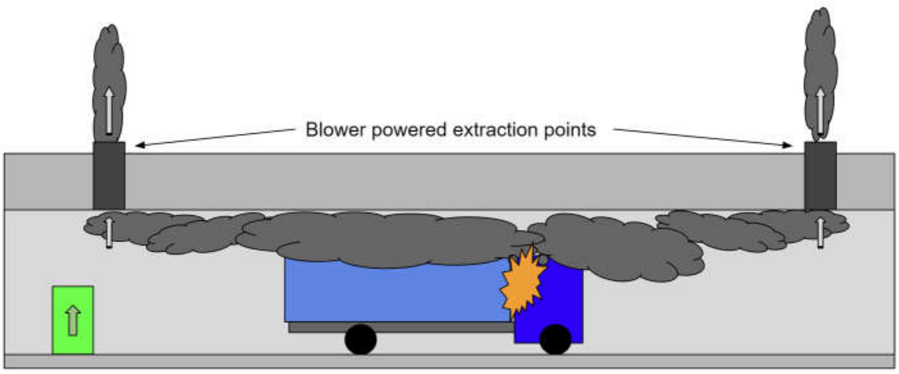

Figure 8: One type of semi-transversal smoke ventilation with extraction points

Li and Ingason (2016) researched road tunnel ventilation with and without extinguishing systems. Mentioning that fire growth rate increases linearly with longitudinal ventilation velocity, and that during evacuation the use of low velocity results in reduced heat release rate, improved stratification and lower risk for fire spread to nearby vehicles. Their conclusion was that to support evacuation in congested tunnels, the chosen ventilation velocity should be at minimum. Suggesting ventilation velocity of 1,5 to 2 m/s for tunnels with queue downstream. When there is no queue downstream their recommendations is approximately 3 m/s to control backlayering, and for when firefighting is started the velocity is preferred to be set at 3 – 3,3 m/s, to prevent any backlayering, reducing concentration of toxic gases and improve visibility far downstream (Li & Ingason, 2016).

Though ventilation has a potential to compete with the suppressions systems, tests show insignificant effect of ventilation on fire development after activations of suppression systems. From the perspective of fire development, the ventilation is said to have limited influence in the range of 1,5 – 3 m/s after the activation of suppression systems with the designed capacity. Where suppression systems decrease the risk of fire spread significantly and that the influence of ventilation on the fire development is expected to be insignificant with such systems, a ventilation velocity of 3 m/s is preferred, mainly to reduce toxic gas concentration downstream (Li & Ingason, 2016).

2.4.4 Water access for fire departments and Extinguishing systems

When the fire departments need additional water for fire extinguishing, the most supportive way to their firefighting is a network of water access points, not involving resources like tankers to transport water between the water source and the fire scene. According to the EU directive (2004/54/EC, 2004), hydrants should be at least every 250 meters for tunnels longer than 500 meters. In Sweden, however, the requirements are at least 150 meters for new and 250 meters for existing tunnels (Gehandler et al., 2012). Lönnermark & Ingason (2004) wrote that the knowledge of how much water is needed to extinguish these kinds of fires is minimal, and theoretical calculations indicate that 1250 l/min is required to control a 100 MW fire. There is a much need for dimensioning what extinguishing capacity the fire department needs when fighting these kinds of fires.

For limiting the fire development and spread of fires, a fixed firefighting system FFFS can be very effective, potentially changing scenarios from catastrophic to manageable. This can also positively affect other objectives, such as evacuation, load-bearing capacity, and the rescue service, as the fire, in general, will be smaller (Gehandler, 2020; Mawhinney, 2011).

Fixed firefighting systems (FFFS) tests have shown that the gas temperature can be decreased significantly with manual or automatic activation. However, the right choice and amount of nozzle are essential (Li & Ingason, 2017). Tests done by Ingason et al. (2014) in the Runehamar tunnel, including one type of FFFS, showed how the fire development is suppressed; one test ended in being free burning and therefore functioned as a base for comparison, with maximum heat release rate at 70 MW, the ceiling temperature, at a distance of 9 meters, raised over 1300°C. With the correct and functioning activation of FFFS, the heat release rate was below 20 MW, even if the activation time was delayed. One measured parameter was heat flux toward a target located five meters downstream. In the free burning test, they measured the heat flux on the target, 39 kW/m^2, but when the FFFS was correctly activated, it was measured well below one kW/m^2.

2.4.5 Traffic control and communication

Effective routes toward tunnels from the closest road must be effective so that the responding units are not delayed. When closing tunnels in case of emergency, the experience from the fire department in Stockholm is that without physical barriers closing the roads toward tunnels, drivers will seek to drive through even if they are signaled that the tunnels are closed (Ingason et al., 2005).

The emergency dispatch center is to obtain correct information from the callers and share that information as quickly as possible, to dispatch the right type and number of resources to the right place. This process required, in turn, an informed understanding of what mattered for each of the organizations that would be dispatched to work in the tunnel (Eklund et al., 2022).

As mentioned in section 2.4.3, modern equipment can automatically detect many abnormalities. The same equipment can also support better traffic flow and register vehicle license plates, sizes, and locations in tunnels (*Smart Tunnel Integration*, n.d.).

2.4.6 Emergency Exits/Access

Emergency access for firefighters is about providing access to tunnels in an emergency, and it is generally considered costly, and the benefits are difficult to estimate (Gehandler et al., 2012). When looking at the safety of evacuees, emergency exits aim to offer the users the means to reach a place of safety in the event of a fire. Preferably this means evacuees are not exposed to falling objects or physical obstructions, high temperatures, high heat flux, high levels of toxic gases, or poor visibility. However, it is thought that the distance is likely less important than convincing tunnel users to leave their vehicles and quickly initiate an evacuation (Gehandler, 2020). In Kim et al. (2010) report on effective firefighting operations in road tunnels, they mentioned that limited access to a fire is the main problem for road tunnels.

In the Proceedings from the 9th international symposium on tunnel safety and security, Woodburn and Antonellis (2020) presented data about firefighters access to tunnels for trains; however, those tunnel sections have some similarities with the setup to city tunnels, where access points for BA-teams are mainly from the side to the tunnels under fire and forced ventilation in one direction. Their calculations showed eight minutes of increased time to perform fire extinguishing when the distance between access points is decreased from 500 meters to 250 meters. The fire source is too close to an access point to be used, meaning maximum travel distance (see figure below for explanation).

Palm et al. (2016) tested different firefighting technics when approaching the fire source and extinguishing fires; these tests included measuring the movement speed of BA-teams while building up standard hose systems simultaneously. The result showed an average movement speed of 0,1 – 0,2 m/s.

Their tests also show how likely some hiccups can occur during the BA operations and building up hose systems simultaneously (Palm et al., 2016). These tests show similar results for movement speed as the results from Ingason et al. (2005) report about rescue operations in road tunnels, where BA-teams were tested both in a smoke-filled tunnel with empty hoses and a smoke-free tunnel with water-filled hoses. In the first mentioned test, the movement speed was measured to be 0,07 m/s and 0,3 m/s, respectively (including building up the hose system).

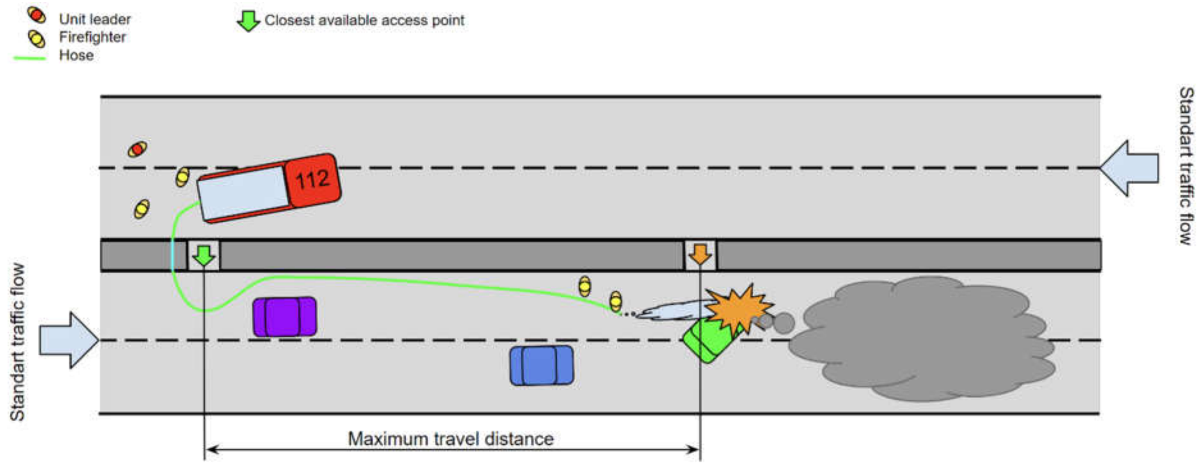

Figure 9: Overview of twin-tube tunnels, showing the meaning of maximum travel distance.

The time available to perform a rescue intervention for BA-teams depends on the time needed to move in a toxic environment to the fire source and their BA-teams air capacity (see section 2.2.2).

2.5 Regulations affecting firefighting

This section presents the difference in the Nordic countries regulations regarding safer and more efficient environment for firefighters during firefighting in twin-tube road traffic tunnels with one-way traffic in each tube.

In all the Nordic countries, regulations regarding road tunnels longer than 500 m that is part of the Trans-European Road Network (TEN) network are based on the minimum safety requirements from the European Union (2004/54/EC, 2004). Only Norway and Sweden seems to have additional requirements and guidelines to fulfill higher safety levels of their tunnels. The table at the end of this section shows comparison of appropriated regulations in the EU directives and countries-specific regulations.

2.5.1 Denmark, Finland, and Iceland

European EU 2004/54 minimum requirements are to be fulfilled for road tunnel constructions.

In Iceland (895/2021, 2021), as an additive, tunnels are commonly built to fulfill the Norwegian N500 standard.

2.5.2 Norway

In N500, the Norwegian regulations (N500:2022, 2022), tunnels longer than 500 meters are divided into six categories (see figure below) after the tunnel length and speculated traffic amount in 20 years.

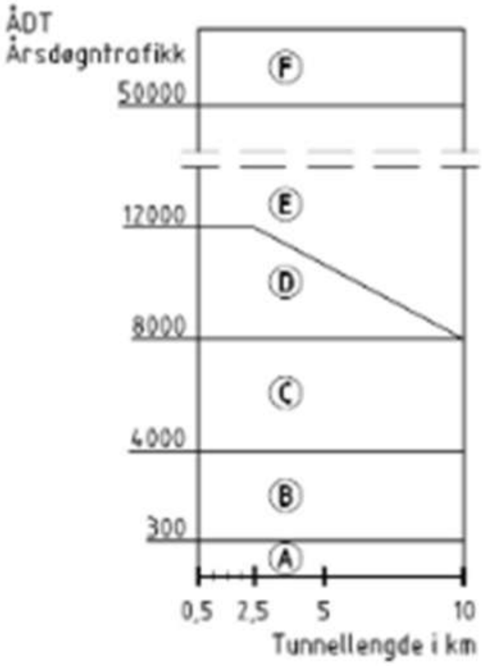

Figure 10: Tunnel classes (N500:2022, 2022)

2.5.3 Sweden

In the Swedish regulations TRVINFRA-00233 (TRVINFRA-00233, 2021), tunnels longer than 100 meters are divided into three categories (see figure below) after the tunnel length and speculated traffic amount in 15 years.

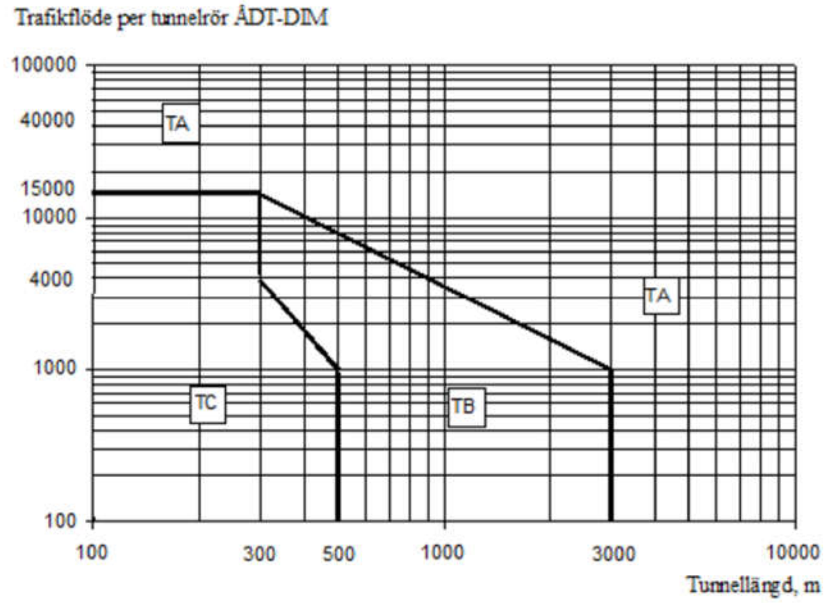

Figure 11: Tunnel classes (TRVINFRA-00233, 2021).

The class is raised upwards, for each of the following factors that is relevant for the tunnel,:

- High frequency of heavy goods transport
- Transport of dangerous chemicals allowed
- Pedestrians or bicycles in tunnels
- Possible congestion in tunnels

For tunnels with level crossings, exits, or entrances in tunnels, complex alignments, or located in open water, the minimum class is TB. It is possible to lower the class for simple alignment or shorter tunnels.

The Swedish regulations require that tunnels are designed so emergency services are given the conditions to carry out operations to save life, property, and the environment, which means that the design will need to involve the safety of emergency services as well as providing them with good possibilities to achieve their tasks.

As guidance to fulfill that requirement, the following is written.

- Utilization of escape routes as access points
  This sentence guides the designers in building the emergency exits to be used as emergency access for emergency services.
- Distance between access points
  Meaning: To keep the distance between emergency exits to allow BA-teams to reach the fire source and search for evacuees needing assistance.
- Extent, design, and load capacity of access points

Meaning: To design the access points meant for emergency services to withstand and hold their integrity in case of fire. That can involve an empty pipe (dry pipe) to guide pressurized water between tubes without smoke moving between tubes through the access points.

- Access to water for firefighting
  Meaning: To integrate water supply for firefighters, to get water to their vehicles, raising the pressure and leading it to the other tube.
- Installations for emergency service communications
  This means: If their communications system is fragile in the tunnels, equipment to strengthen the signal will need to be installed.
- Drainage system for hazardous liquids
  The drainage system should be able to gather all hazardous liquids leaking on the surface without the risk of spreading further in the tube or to the other tube. These systems will then minimize the possible spillage and that it is ignited.
- Additional measures to facilitate rescue efforts.

Installed equipment necessary for firefighting should handle temperatures up to 250°C.

In the table below the EU minimum requirements for road traffic tunnels are compared with the Norwegian and Swedish regulations, if the box is left empty, nothing regarding the matter was found in the countries specific regulations and therefore the minimum EU requirements should be in place. If the box belonging to the EU regulations is left empty the countries specific regulations is covering matters that the EU minimum requirements are not found to cover.

Table 2: Comparison of differences between EU directive, Norwegian and Swedish regulations that affect the safety and effectiveness of firefighting.

	EU 2004/54	Norway	Sweden
Design fire development			Based on risk analysis for TA and TB classed tunnels, 180 min, HC development.
Twin-tubes or more with one-way flow traffic	AADT >10000 veh./lane in <15 yr.	Tunnel classes E and F	
Gradients of the road in a longitudinal direction	< 5 % if possible		> 3% requires risk analysis for approval
Emergency exits (Access)	< 500 m between if traffic is > 2000 veh./lane	< 250 m between exits	If longer than 200 m in > 300 m tunnels, minimum criteria of sight, heat-flux,

			and temperature must be met.
Cross sections for emergency services	Every 1500 m in tunnels >1500 m		
Crossing of the central reserve outside each portal	All tunnels	All tunnels closed with a remote-controlled gate	
Drainage for flammable and toxic liquids	If ADR is allowed		If ADR is allowed, the drainage system should handle ignitable liquids without the risk of further fire spread.
Fire resistance of structures	If local collapse could cause catastrophic consequences		Detailed description for tunnels > 100 m where AADT is > 100
Mechanical ventilation	AADT > 2000 veh./lane, tunnel > 1000 m	Tunnels > 1 km and AADT > 1000 in 10 yr.	Class TA and TB, risk analysis to choose the type.
Minimum ventilation velocity in case of fire		Class related, 50 – 100 MW, HC development, 60 min, 3 – 4,5 m/s	Dimensioned to prevent backlayering and provide safety for evacuees and firefighters If > 1000 m or AADT > 4000 and longitutional, min velocity is 3 m/s for 100 MW
Water supply for the fire department	< 250 m	There must be a water supply with municipal pressurized water	Tunnels > 300 m = 250 m between and close to emergency exits
Control center	Traffic > 2000 veh./lane, tunnel > 3000 m		Traffic > 4000 veh./lane, tunnel > 3000 m

Video monitoring systems	Traffic > 2000 veh./lane, tunnel > 3000 m		Tunnels classed as TA and TB.
Equipment to close the tunnels	Signals in tunnels > 1000 m	Class C - F tunnels and A, B if needed by risk analysis	Tunnels classed as TA and TB
Risk analysis required	In case of abnormalities like ADR or >3 % gradient	All tunnels > 500 m	All tunnels classed as TA and TB
Fixed firefighting system	Not involved		Should be installed if risk analysis shows increased safety
Traffic control system			Tunnels classed as TA.
Radio signal coverage for the fire department			In tunnels > 500 m, the fire department is supposed to be able to use its communication system.
Smoke moving between portals in smoke ventilation.			Safety measures must be in place.

3 Interview study

In the following chapter, the methodology of the interview and how they proceeded is described.

3.1 Method

In this section, the method used for the research is introduced. This includes a literature review where previous research and published articles are studied, preliminary interviews conducted, and interviews with experts in tunnel management (TM) and firefighters (FF). Finally, the data was analyzed and discussed. When the literature study was conducted, this resulted in new questions for the interview guides (see Appendix 1 and 2), which were then used in the main interviews, as the table below demonstrates:

Figure 12: Research plan during spring semester 2023.

A qualitative interview study was used to gather information from individuals with experience in tunnel firefighting and individuals with experience in tunnel management. The aim was to gather data about their profession, experience, and viewpoints regarding firefighter safety and efficiency when fighting fires in tunnels in Nordic countries. The interviews were aimed at specific geography, the Nordics. Preliminary interviews were conducted with professionals from Iceland; interviews in this study were taken from professionals from Denmark, Sweden, Norway, and Finland. The reason for choosing participants from those countries is that they are considered highly developed, and education and institutional guidelines are considered relatively similar, compared to other European countries. With that in mind, particular interest was in similarities/differences between tunnel managers and firefighters in the Nordic.

3.2 Interviews

The interviews were chosen to be semi-structured, which means interview questions are structured in a professional conversation with specific goals and techniques. The interview guide was formed after the literature search, where relevant gathered information regarding firefighters, firefighting operations, and tunnel management was used to structure the questions. Since two different professions were interviewed with different roles in fire tunnel safety, two semi-structured interview guides were used.

One for group 1 (FF), firefighters (see Appendix 1), and one for group 2, tunnel managers (TM) (see Appendix 2). Each interview guide focuses on specific themes and suggests questions (Brinkmann & Kvale, 2015). After the interview guide was structured, preliminary interviews were conducted. Three meetings with specialists in Iceland were conducted for further development. Two interviews with firefighting experience, one meeting with the head of the operational department in Greater Reykjavik Fire and Rescue Service, and one meeting with the head of the fire prevention department in Greater Reykjavik Fire and Rescue Service. For the interview guide for individuals with experience in tunnel managing, a meeting with four specialists at the Icelandic Road and Coastal Administration was conducted. After receiving feedback from the interview questions, the interview guides developed further.

The next step was to find participants for the interviews in the Nordic countries, preferably with the criteria for a twin-tube tunnel in their area. The table below shows how many participants came from each country:

Table 3: Shows where the participants came from and their backgrounds.

	Danmark	Finland	Norway	Sweden
Fire department	1	1	1	2
Management	1	0	1	2

4 Interview analysis

In this chapter, the nine interviews are analyzed. As demonstrated in the method chapter, interviewees are divided into two groups; Group 1 consists of experienced incident commanders from fire departments (referred to as FF participants hereafter), and Group 2 of experienced individuals regarding tunnel management, tunnel safety design, referred to as tunnel operators (referred to as TM participants hereafter). The following sections emerged from the data related to tunnel fire safety and interviews. Summaries from each interview are presented in Appendix 3.

Participants representing incident commanding in tunnel emergencies had experience of 5 – 30 years regarding incident commanding at different command levels. Their area is different in the number of tunnels they service.

Participants representing tunnel management and safety specialists had experience of 10 – 30 years regarding safety measures in tunnels, working for tunnel owners, both individual corporations and governments.

4.1 Collaboration during design of new tunnels and emergency plans

All participants with experience with train or metro tunnels in their area said they are more dangerous and difficult to approach. Four out of five FF participants stated that the fire department works closely with the designers in the early stages of new tunnel projects; one said they only get involved in later stages. However, they all want to be involved early in the process for their expertise to be heard. FF participants feel like their concerns are being listened to regarding safety measures. TM participants had a similar experience where they communicated well with the local fire department for emergency planning and equipment setup. During the design phase, TS participant mentioned good dialog between road tunnel traffic authorities specialists and tunnel designers. However, in that case, the fire department is not included until later. Finally, one FF person mentioned that their fire department does not want any special tunnel-related equipment as their own, and the necessary equipment should be included in the design. In both groups, interviewees mentioned that good communication and dialogue were essential to developing fire safety in tunnels further:

[…] We also have a tight dialogue with the rescue service. We have a forum where we meet at least twice a year where we look into all types of issues. We look at the incidents that have happened; we look at the exercises that we have done and the plan for the next exercise. We also look at new tunnels and how they are affected by those experiences that we can see from the existing tunnels, so I think we have quite a good dialogue.

(TM participant).

Collaboration between different parties in the fire safety tunnel industry seems, therefore, important for effective emergency management, regardless of what background the participant has.

4.2 Tactics and Exercises

When asked what tactics are practiced when responding to emergencies inside twin-tube tunnels, the primary outcome is that most city tunnels in the participants area have response units arriving from both tunnel ends. If there is a confirmed fire in tunnels, one to three firefighting units are sent inside the unaffected tube, arriving from both ends. At the same time, other response units are supposed to halt outside the portals for further instructions.

We always send one to three fire trucks into the tunnel and one fire commander into the tactical rooms.

(FF participant)

They prioritize lives saving operations by assisting evacuees in distress, suppressing, and extinguishing the fire. In all scenarios, the unaffected tube is used to reach the needed depth in twin-tube tunnels before entering the affected tube. Furthermore, BA-teams use emergency exits for moving between tubes. FF participants mentioned that the first unit arriving enters the affected tube with BA-teams through an available access point upstream of the fire, as close to the fire source as possible, to have the ventilation direction in their back.

The first fire station goes upstream the fire from the unaffected tube; the second fire station goes downstream. That is the basic principle. The third fire station is on the surface in a standing point and used to be put in where it is needed. Then you have one fire station upstream fighting the fire with the wind in the back, and the second fire station is downstream, searching for eventually trapped victims. And then you have two commands […] also at a suitable command post. […]But the basic principle for all tunnel fire incidents is to make an attack from an unaffected area, so we never drive into a tunnel that is on fire.

(FF participant)

Other crew members connect their vehicle to water access and back to a connection on the wall, allowing pressurized water to flow to another connection in the affected tube, a dry pipe between tubes. The BA-team can then build up their hose system from the connection in the affected tube and begin their operations. The benefit of such dry pipes between tubes where commonly mentioned. By such installation, firefighting units are not forced to keep the access point doors (emergency exit doors) open for the hose, possibly enabling smoke to flow between tubes. All FF participants stated that they aim to use regular water during their operations but that they also have alternatives on their trucks if needed. In addition, all FF participants mentioned that their BA-teams are equipped with infrared cameras; in some cases, each firefighter has one, while in others, there is one camera per team.

The unit arriving from the upstream side aims to extinguish the fire or get to the source of the incident. The unit arriving from downstream starts with helping individuals evacuate. In some cases, the second and third unit is sent as a support team towards the unit at the incident source.

(FF participant)

Interestingly, all participants from fire departments seem to use similar tactics when responding to tunnel fires in the Nordics. This showcases that tactics and exercises are coherent between countries in the Nordics. Some participants mentioned the importance of knowing where and when to fill up their water hoses; if they are filled too far from the fire source, they must empty them again before moving the primary connection and the whole system. A hose system full of water is too heavy to move around.

Some new tactics have been tested related to tunnels; as a participant mentioned, where tests regarding metro tunnels, the fire departments used teams for reconnaissance to locate the source and give back better information quickly. That includes sending the first BA team into the tunnel without water hoses, only carrying an extinguisher, and connected to a light "life" line with integrated LED lights. By doing so, the BA teams can advance much faster, locate the source and give feedback to their commander. The incident command can then make better decisions on tactics and resources. As mentioned, participants with metro and train tunnel experience think they are more challenging to approach and not surveilled in the same amount as city tunnels.

Participants, experienced with control rooms near the tunnel portals for incident command stated that their incident commanders tend to use the traffic control center to adjust tunnel equipment settings, even if they can adjust it in those rooms. However, participants also noted that if access to surveillance cameras and radio announcements in these rooms is available, it is considered very efficient and used by incident commanders.

TM participants mentioned that their tunnels are not designed with special operation rooms for the incident command near the portals. The incident commanders control operations from the fire truck or special incident command vehicle and change equipment functions via radio or cell phone communications with the tunnel control central. It was thought to be more efficient where there are relatively few incidents per year, and it is more accessible for the incident commander to ask a more experienced staff of the tunnel control central to fulfill operational goals regarding equipment control.

One TM participant described the procedure for the first phase of their systems function after the tunnel traffic control confirmed a fire inside the tunnel and marked the location in their program. All the following functions start simultaneously:

- Lightning brightens up
- Ventilation starts at 1,5 m/s
- Barriers outside close the tunnel

- Evacuation information is sent to users of the tunnel

FF participant mentioned that his fire department uses OBA equipment during BA operations in tunnels; this type of BA equipment gives up to 4 hours of air, while standard air bottles that other participants claimed to use give firefighters 20 – 30 minutes of air, when other participants where asked why they do not use OBA, some mentioned that they are heavier and required more maintenance and exercises to function correctly. Another FF participant, where standard BA equipment is used, mentioned that all his firefighters have the knowledge and equipment to double up their air capacity for extended BA operations.

All FF participants mentioned that exercises are too few and that giving all firefighting personnel experience through exercises so infrequently is challenging. In most cases, there are exercises yearly; one participant mentioned having lighter exercises every other year and more extensive exercises. All participants mentioned that exercises proceeded with simulations of real scenarios using cold smoke production, therefore not the same smoke behavior as smoke from burning material. Furthermore, all the participants mentioned that their more extensive exercises included tunnel control personnel, police, and ambulance services. Interestingly, two participants, one from each group, mentioned having a tunnel only meant to exercise firefighting personnel with burning material, and therefore, they experienced a realistic environment for training. Tunnel exercises in those tunnels are a part of their national firefighting education.

FF participants thought it is crucial that traffic control center operators are well trained and that their knowledge of how the different systems work is of the essence for firefighting operations.

When asked if there are availabilities to move rescue vehicles between tubes every 1500 meters for tunnels longer than 3000 meters, as the European regulations require, there is a difference in how to interpret that. One interviewee said the fire department never wants to move the fire trucks into tunnels under fire; therefore, the emergency exits/entries fulfill the goal, while another FF participant mentioned that they had this installed in one of their tunnels but disconnected its opening function due to maintenance difficulties for these large fire rated doors and low usage.

Concerning tactics, two interviewees in the group mentioned protocols that alarm the tunnel control system. In their system, the alarm reaches the police, the fire department, and the closest emergency hospitals. That gives the hospitals time to prepare for multiple casualties if needed. However, this is possibly done elsewhere and by other response centers. For smaller communities with hospitals, this can give their personnel time to prepare and call in personnel if needed. For more significant scenarios, they would be prepared for critical individuals transported from the incident, both users and firefighters.

One TM participant with nearly three decades of experience in technical installations for tunnels mentioned that, in his opinion, the essential safety factor for evacuees and firefighters is to have twin-tube tunnels with one-way traffic flow in each tube. The interviewee also mentioned that tunnels are constantly getting more technical with equipment that can solve other equipment roles. However, there is a tendency to keep all older installations as well. Interestingly, one interviewee stated that the equipment being used today is sufficient; mentioned that there is a need to strengthen the link between equipment and the organization; the tunnel control center and the fire department should have excellent knowledge of how the equipment should work and how they know it is working. Too often, there is too much difference between tunnels. For example, the participant mentioned that how the ventilation is controlled varies between meters per second, percentage of output power, or pre-defined steps.

Surveillance systems, a well-designed ventilation system, fixed firefighting systems, and experienced tunnel control center personnel can save lives during tunnel emergencies. Their ability to support the fire department in safety and efficiency during operations is significant. Therefore, all procedures must be well structured and approved by the local fire department. Exercises should be held regularly, and it is in the owners favor to fulfill this task, which impacts the communities thoughts of tunnels and the possibility of shorter downtime if the right reactions are made during emergencies.

Overall, all participants feel that the modern twin-tube tunnel design is on a good path providing safety and supporting their efficiency for firefighting. In the interviews, however, it is important to note how tunnels are constructed, how they are used, and for what purposes. This can influence tunnel safety, as this quote illustrates:

Swedish TS participant mentioned that fighting the fire in those tunnels can be more straightforward than on open roads, referring to twin-tube tunnels. In these newer tunnels, the wind direction is controlled, the location of extra water is known, and, in some cases, they are equipped with fixed firefighting systems.

It is even easier to deal with the fire in that type of tunnel than on the surface. Because you have everything planned for you. You have a special direction of the airflow, you know where you can get water, and sometimes even have a fixed firefighting system. So I think it is very well organized for them.

(Swedish TM participant)

I do not see much need for the road tunnel; I think they are very safe tunnels with good possibilities for us to make our response in the tunnels. But in tram or railway tunnels, it is definitely room for improvement.

(Swedish FF participan)

This can indicate that the possibilities to perform well-structured, safe, and efficient operations are good in modern twin-tube tunnels in the Nordics, as the following quote from a Swedish FF demonstrates:

Say when we lead the response from operation rooms with the monitors so that you can see the whole tunnel system 6 or 8 images from different places in the tunnel system and the overall layout of the tunnel, and so on, the wind direction in the tunnel […] what capacity in the ventilation fans are working in. […] I think it is very good. That we have a separate room not affected by the tunnel of the incident, and so on […], we have very big possibilities to have a look at all the parts of the tunnel at the same time so we can watch our personnel in the safe area and the incident in the tunnel in the other two, both the entrances to the tunnel so we can have a very good overview over the whole concept.

(FF participant)

4.3 Fire development and heat Flux

None participants had experienced fires in heavy goods vehicles or multiple smaller vehicles in their tunnels. Most incidents involve fires in smaller personal vehicles; however, a camper van ignited in one case. In that case, the tunnels were equipped with FFFS, which suppressed the fire development. The participant that experienced the camper van burning said that incident analysis was conducted, where the expected heat release rate if FFFS had not been activated, could have been around 30 MW. However, with the activation of FFFS, it was thought to have resulted in 10 MW and, therefore, a more straightforward task for the fire department to extinguish. Therefore, none of the participants had experienced firefighter retrieving because of high heat flux from fires in twin-tube tunnels.

4.3.1 Concrete spalling

When FF participants were asked if spalling in a tunnel would affect their operations, all but one answered that it would delay their operation while risk assessment was done.

They certainly will halt. For a moment and report to the commander, and we will make an overall assessment of the risk, risk analysis, before we carry on. It is possible to keep going, but we have to make sure that we can do it in a safe way. We do not immediately retreive.

(FF participant)

When asked if they had such an experience, one participant mentioned experiencing it during an experimental test.

4.4 Detection and surveillance

When participants are asked what type of equipment is used for detection in their tunnels and their opinions regarding different equipment, the importance of surveillance cameras that fully cover the tunnels is frequently mentioned. An incident commander with well-covered surveillance in their tunnels and other tunnels with only portal surveillance said it significantly impacted the operation and decisions to have accurate information from the traffic central, which they can provide with better surveillance systems.

Tunnel control can sweep through the tunnel with their cameras very quickly and see if there are any people evacuating, and that is part of our tactics to the second or third unit that arrives at the tunnel […] to look for evacuees or ensure that there are no people in the smoke.

(Swedish FF participant)

When there are no surveillance cameras inside the tunnels, the only way to know if there is a signal of life and their location is to surveil the detection of fire extinguishers removal, emergency doors opening, or if emergency phones are used.

Some firetrucks seem to be able to receive video streaming feed from the traffic control centers, which is thought to help the commander to gain grounds for operational decisions. In most cases, the fire departments operation centers receive surveillance video feed during emergencies.

We stream all our live feed videos directly to the Fire Brigades rescue central, and then they can ask for other views. So we are cooperating very close there. The next step is that the fire commanders themselves could get those pictures out to the command vehicles, but we are not there yet.

(TM participant)

According to all participants, surveillance cameras are primarily located in the ceiling and lose sight downstream quickly when smoke builds up. In one tunnel mentioned, the surveillance cameras are located on the wall where the tunnel height is insufficient for ceiling installation. One participant describes the function of how surveillance systems and communications can support their safety regarding driving against normal traffic flow:

So if we need to go into the tunnel that usually has the traffic against us, we have a dialogue with the traffic controller commander, and when he says that all the traffic in the tunnel is empty, we can open the booms and go against the traffic flow.

(FF participant)

During the interviews, it becomes clear that detailed information is needed from the tunnel control central regarding the incidents. According to one participant, there have been incidents where the responding vehicles drove into the tube under fire.

Some difference is between the quality of images from surveillance cameras in the Nordic tunnels; one TM participant mentioned that the tunnel center operators could identify ADR markings on vehicles and even software registering the vehicles in and out of the tunnels. While all others from the same group mentioned that their system has good identification possibilities regarding the type of vehicles and that they could possibly identify if the orange ADR plate is on the vehicle but without identifying a specific number. One participant mentioned that some of their tunnels have digital and thermal cameras in all surveillance points, providing better ways to identify individuals or vehicles in smoke-filled tunnels.

We have cameras that read the ADR plates on the vehicles, so we have a list of what we should expect.

(TM participant)

All TM participants mentioned integrated automatic detection in their camera surveillance system. They seem, however, to have different detection levels; some only detect stopped vehicles, while others detect all abnormalities like sudden speed changes, smoke, wrong traffic direction, or pedestrians; when the system detects an abnormality, the video feed prompts on the screens in front of the tunnel control center operators. Based on data from the interviews, it was evident that tunnel operators have a great possibility to support the fire department during their operations; and to do so, they rely mainly on their surveillance systems. From detecting the hazard, controlling, or closing for traffic, following through the evacuation process, guiding the response units to the correct locations, and ensuring no traffic flows against emergency vehicles.

All of the participants mentioned that their surveillance cameras are located in the ceiling for best overall coverage; in case of a fire, they will lose sight downstream when the smoke layer builds up; in one case, the participant mentioned that his authority is looking into how and if this can be improved.

Some tunnels are mentioned to use combination alarm systems, where combinations of preprogrammed detections result in an alarm. This can, for example, be low oxygen levels along with a camera with low visibility and an emergency exit opened or a vehicle stopped along with an emergency exit opened and a temperature rise. According to one interviewee, there have been some false alarms in this type of detection. Some participants mentioned that their tunnels have automatic smoke detection equipment in the technical rooms that immediately alarmed the fire department; in some cases, however, they are changing the function now and directing the alarm singularly to the tunnel control central. The tunnel control center can then confirm the fire or incident before alarming the fire department.

In none of the interviews, the thermal detection cables installed in many tunnels were mentioned as vital for detection.

4.5 Ventilation

According to the fire departments, there is a difference in ventilation chosen velocities during the phase after confirmation of a fire until the fire department takes over the equipment control, as this quote demonstrates.

The normal thing would be that the ventilation in the tunnel with fire is turned on. As I recall, it is just normal until we are requested by the Fire Brigade management to adjust it.

(TM participant)

FF participant mentioned that when his units arrive at the scene, they never ask for the ventilation to be increased unless they are positive that no evacuees are left downstream, where higher velocity increases the heat flux from the fire. Usually, they only maintain the recommended velocity. While another FF participant mentioned that after the confirmed fire, the ventilation is set to 2 m/s; if the traffic control central sees through their surveillance system that it is insufficient to prevent backlayering, they increase it. When the fire department arrives and starts its approach, the ventilation is generally set to 3 m/s. In addition to ventilation, an FF participant mentioned exercises with mobile fans. Their experience is that they make too much noise, which affects the communications possibilities; they take time to deploy, are not feasible as a quick response, are seldom needed, and are expensive. However, they mentioned that they are powerful and effective.

Some differences in chosen velocity speed for the ventilation can be seen between tunnels and countries. TM participant said it was previously decided to use 1,5 m/s to support evacuation possibilities downstream in one of their tunnels equipped with FFFS. Recently it was decided to increase the ventilation velocity in the same tunnel, right after fire confirmation, to 3 m/s. Using 3 m/s was initially chosen to prevent back layering in case of 100 MW fires in another tunnel, in the same area, with possible traffic congestion. After investigating actual fire incidents, the results from lower ventilation velocity gave lousy visibility, and therefore it was decided to increase the ventilation velocity to 3 m/s even with congestions downstream. By doing so, the visibility is increased, the temperature of the smoke is decreased, and toxins are diluted. Therefore, they conclude that 3 m/s supports the evacuation process and the fire departments ability to extinguish. Their conclusion also included that when ventilation was set to critical velocity speed to prevent back layering or 1,5 m/s, the fire was already getting enough oxygen, so more speed would not increase the fire growth. The interviewee also mentioned that 3 m/s is just below 11 km/hr. Moreover, it did not seem to affect the downstream traffic during evacuation. It would, however, affect evacuees that have left their vehicles for evacuation on foot.

Our exercises have shown that 1 1/2 up to two meters per second in the traffic direction is more than enough.[…] I think it is partly from exercises, design, measurements, and experiences. Besides that, 1

½ meters per second is efficient to ensure people to escape and make give us a good possibility to get close to the fire in a good environment.

(FF participant)

Another interviewee said their ventilation velocity during emergencies is around 4 m/s. However, they are looking into scenarios where they think they will lower the velocity to 3 – 4 m/s to minimize turbulence and keep better visibility. If, however, the fire department asks for a ventilation velocity change, it is changed, as well as when they are using one tube for a two-way traffic flow; for instance, when the other is under maintenance, they aim to use a lower velocity.

FF participant mentioned that when adjustments are needed, they will have to contact their dispatcher and ask them to contact the tunnel control central to fulfill the requirements; in this area, the incident commander has the opportunity to adjust the system on site but tends to use the radio to the tunnel control central instead. This is because of a lack of experience using the controls and trust in the experience of the tunnel control central.

In one interview, the participant mentioned that if they would, by any chance, lose communication possibilities with the tunnel control central, they could use the on-site controls to adjust ventilation settings.

The ventilation starts automatically when there is a fire detection and approximately 1 1/2 meter per second in the direction of the traffic. That is automatic in all the road tunnels, the pipe where the fire is, and the other pipe; it starts pressure so the smoke will not suck in with the fresh pipe.

(FF participant)

When interviewees were asked if they had experienced smoke moving between portals during a fire incident, the answers differed. Most interviewees had experienced this, but some did not; all ventilation systems were set up to minimize the possibility. In one case, according to a TM participant, the first group of jet fans in the smoke-free tube, closest to the other tubes portal venting smoke out, are turned to prevent smoke from moving in. In most cases, the whole ventilation system in the smoke-free tube is turned to ventilate in the same direction as the tube under fire. The participants that had experienced smoke moves between portals during ventilation strategies did; one participant mentioned that it was not a high density of smoke but enough to make the environment in the smoke-free tube polluted.

And that was enough smoke to worsen conditions in the healthy pipe you stay in.

(TM participant)

TM participant mentioned that their jet fans are not explosion-proof, and the tunnels allow ADR transportation; for those scenarios, they depend on pushing strategies with the ventilation and turning the jet fans downstream off. FF participant mentioned the benefits of pulling smoke ventilation strategy to increase laminated smoke flow.

Pull out the smoke instead of pushing it because it is a better environment in the tunnel and less turbulent in the stock.

(FF participant)

Suppose the portals of twin-tube tunnels are closed. In that case, it is thought to be important by FF participants that when in the smoke ventilation phase, both portals are ventilated in the same direction to minimize the risk of smoke moving out of one portal and into another.

4.6 Emergency exit/access, water access and dry pipes

FF participant mentioned that sometimes during the design phase, the construction owner wants to cut costs by having fewer emergency exits or other safety measures. In those cases, they have been open to the suggestions of the fire department. The same participant mentioned that the fire department was shown suggestions for a new tunnel a decade ago, including that the BA-teams were supposed to travel up to 500 – 1000 meters to achieve their task. When the fire department described to the construction owner how their work proceeded, building up the hose system, moving all the gear, and having about 20 – 30 minutes for each BA-team, they realized it was insufficient.

Modern calculations for distances and time for firefighters to extinguish the fire after reaching it from the nearest emergency entry were mentioned by FF participant. He thought they were not representing reality and that the moving speed of BA-teams tends to be lower when the hose system is being built up along with moving towards the smoke. For example, he mentioned that if the distance between emergency entries is 150 meters, it is thought to be the maximum path toward the fire source, which means at least six 25 meter hoses and a minimum of eight couplings just for the attack line. According to an FF participant, regulations in Sweden require that BA-teams have water-filled hoses while in BA operations in a smoke-filled environment.

According to FF participants, those with experience with 100 - 150 meters between emergency entries/exits said it provided good possibilities to reach the scene quickly. FF participants mentioned that even though they have a 250 meter requirement from the EU regulations, they build all new tunnels in their area with around 100 meters between their emergency evacuation routes. That supports quicker evacuation as well as easier access for the fire department.

An FF participant said they could previously drive between tubes in one of their tunnels due to requirements from the EU directive. However, because of difficulties in maintaining these large fire-rated doors and low usage, they were closed. The participant also mentioned that he/she did not see the need for it.

According to TM participants, some tunnel emergency exits have spy holes on the doors or windows; the brightness from vehicle lights or fire can be visible through them and help firefighters determine if the fire is nearby or if there is a risk of moving traffic on the other side.

Typical distances between emergency exits, mentioned in interviews with experience from twin-tube tunnels, are shown in the table below.

Table 4: Distances between emergency exits, mentioned in the interviews.

Interview	1	2	3	4	5	6	7
Distance [m]	100 - 150	100 - 150	80 - 90	250	150	100	100

The maximum distance between hydrants varies between 80 – 250 m; according to interviews, they are always located beside each emergency exit. It seems standard design to include dry pipes between tunnel tubes at the same location to allow the fire department to pump water between tubes without keeping the emergency exit doors open. An FF participant mentioned that the water system for their fire hydrant system is designed to provide 2400 l/min at maximum.

According to the interviews, dry pipes between tunnels are being used and considered necessary by all FF participants, keeping the smoke-free tunnel safer by lowering toxic smoke moving between tubes.

Every transmission connection has its own hydrant and standpipe.

(Swedish FF participant)

One participant mentioned that in their tunnels, dry pipes and hydrants are marked with different colors, red for the dry pipe and blue for the fire hydrant. The marking minimizes the possibility of a wrong connection and time lost in sorting it out. The fire hydrants are the same as those used in the city and, therefore, something that the firefighters are familiar with.

4.7 Extinguishing systems

The sprinkler system is thought necessary by the participants familiar with them; they lower the gas temperature and heat flux, minimizing the possibility of fire spread between vehicles. There are not many incidents where they have been used, but in those cases, they have worked well.

TM participants with low-pressure FFFS in their tunnels spoke highly of their functions and effect on providing a safer environment for the structure, evacuees, and fire department. According to TM participants, there have been few incidents where these systems have been used. However, in those incidents, they played a significant role in minimizing the negative effect of the fire.

[…] he estimated about 10 MW fire in the tunnel. And that was because of the fixed firefighting system; if we did not have the fixed firefighting system, it would have been 30 MW, and we could have had quite large damages […]

(TM participant)

The installations of FFFS in tunnels seem to influence the fire development significantly and, therefore, the scene development, with some great benefits.

4.8 Communications

Interviews indicate that communications are vital to support the right decisions regarding strategy, the route toward the scene, and needed resources. The primary focus seems to be communications between the scene commander and the tunnel control center operator during the communications.

As soon as they detect any situation, they type it into a system […], Which is a safety management system. That immediately gives the same information to all the responders, which includes the police on both sides and the fire departments on both sides, and also the hospital on both sides.

(TM participant)

According to TM participants, there is some difference in how tunnel control centers alarm the fire departments. However, in all cases, it is said to have good function.

The most vital information is which of the tubes is involved, which city, and which is the closest transverse connection, so we can go in the fresh pipe and stop at the transverse connection. […] And of course, what type of incident […] if the tunnel is closed according to the checklist that we have had planned.

(FF participant)

An FF participant mentioned that they use cell phones to communicate directly with the tunnel control central; if they are to use the radio, they have to do it through their dispatch center. In some incidents, the barriers between portals have delayed their fire trucks because of poor communication, and they could not open them manually.

All FF participants said that communication signals functioned well in their tunnels, and all recalled that some signal boosters were installed where needed.

4.9 Drainage systems

According to participants, pumps for draining out the drainage system are shut off to prevent contaminated liquid from flowing into the cities drainage system in case of fire or chemical leakage. Some FF participants mentioned that well-designed drainage systems minimize the spill size and should not allow the leakage to drain along the tunnel for longer distances.

TM participant mentioned that drainage systems should be able to gather the whole leakage without overfilling and that Swedish regulations require drainage systems to support prompt liquid disappearing, with the capacity to allow 10 m^3 dropped simultaneously to disappear from the road surface in 2 minutes.

4.10 Traffic control

All participants agreed on the importance of traffic control towards the tunnels during incidents but also to look at how the traffic could flow downstream from the fire during the evacuation phase. According to TM participant, this work has started in his tunnels, and it is being analyzed if the tunnel control center can have the availability to close adjacent traffic lanes to allow a better flow of vehicles out of the tunnels. This is thought to give evacuating traffic downstream from the fire a better possibility to evacuate before the smoke reaches them. This is also thought to free up the smoke-free tube quicker, allowing response units to use it without any vehicles inside.

Other TM participant said this has been looked at, and the result is that it would affect too large an area with congestion. TM participants also mentioned that this could be harder to solve if the tunnel control center is not under the same jurisdiction as the cities traffic center. However, another participant, where the tunnel control center, said they could close and free up traffic lanes leading toward their tunnels.

All the twin-tube tunnels in the participants area are said to have physical barriers that the tunnel control center can remotely close. Some FF participants mentioned delays in arrival time due to traffic congestion on traffic lanes leading toward the tunnel portals. Moreover, this could delay the arrival by some seconds up to minutes. TM participants agreed that congestion in heavy traffic areas could be a problem during emergencies, but as one participant mentioned:

When you have a twin-tube tunnel, it is two lanes to drive [...], and it is not so often, rarely, almost never that both lanes are full.

(TM participant)

4.11 Tunnel signals and lightning

FF participant shared good experience of locating what emergency exit to use and suggested from the tunnel control center; in those cases, all exits are marked with individual identifications, visible from both traffic directions. However, in some cases, FF participant described difficulties receiving information on which tube to use for safe entrance. In that case, each tube has a full name for identification. One FF participant said they have good experience with signals standing out from the wall above each emergency exit. With that setup, the sign faces the firefighters when driving along the smoke-free tube.

The way they are directed is by radio, but also we illuminate a light on the door that they are supposed to enter.

(TM participant)

One TM participant said their operators could illuminate the emergency entry closest to the fire source, making it straightforward for the fire department what entrance they should use.

4.12 Other equipment

Some fire departments seem to have special vehicles aimed at tunnel firefighting; for example, ATVs, small narrow vehicles, and tankers with water canons were mentioned. Otherwise, FF participants mentioned that they aimed to use the same equipment as in other firefighting operations, where that is what they know how functions and are more commonly exercising on. The participant that mentioned using specially equipped tankers for tunnel fires mentioned that there is no water access on their tunnel site. These tankers are also used in other incidents when water transport is needed, therefore, they are not special equipment for tunnel-related emergencies; the same goes for ATVs, also used in wildland operations.

Normally the fire brigade they have the option to connect their truck to a power outlet and turn off the engine. They never do that; they tend to use their own diesel generator. Because they know it works.

(TM participant)

One TM participant mentioned that their tunnels have power outlets for the fire trucks to connect to, but they are never used. The fire department tends to use its equipment for generating electricity if needed.

5 Discussion and reflection

The following chapter discusses how to involve firefighting tactics in the design phase of new tunnels to provide increased safety and improve their efficiency when responding to emergencies in twin-tube tunnels. The discussion has been categorized into themes identified in the literature and during interviews for better clarity.

5.1 Limitation

The literature search was focused on firefighting in road tunnels. However, literature is available regarding factors relevant to firefighting in tunnels, even though it is not with that focus. For example, what water flow, is needed for extinguishing different vehicle fires, such as batteries in electric vehicles, hydrogen-powered vehicles, heavy goods vehicles, and flammable liquid spillages. Even the expected work duration of BA-teams in other types of tunnels can be relevant. The interviews only capture a limited range of personal perspectives and perspectives from specific countries. While the interviews offer a convenient way to access up-to-date practices and expert opinions, their results cannot be seen as a general opinion for their profession and only reflect the viewpoints of the particular experts or groups of experts interviewed. Additionally, interviews should not be compared due to the different interview guides and the semi-structured interview method.

The results from this study can assist tunnel designers in integrating firefighting into tunnel design and increase the knowledge of possible problems new twin-tube tunnel structures can involve when emergencies occur.

5.2 Collaboration during design of new tunnels

An easily accessible, open dialog regarding tunnels between countries would support evaluating firefighters safety and effectiveness, where new ideas, methodologies, and experiences could be shared.

It would only be for improved safety and efficiency to have the fire departments involved early in the design phase or at least open dialog with them; it is, however, important that when fire departments are to be involved that they have well-informed personnel regarding the matter to improve their effectiveness in the collaboration. To support their safety and efficiency, they should have opinions regarding what chosen scenarios are realistic to represent expected fire development, the maximum heat flux they are capable of working in and how close to the source they need to be for firefighting, what type of smoke ventilation they prefer, their requirements for smoke ventilation abilities, and programming, what moving speed they are confident that their BA-teams can achieve, and the duration time for BA operations, location for water access and what type of connections they prefer, the needed water flow for expected fire development, how they prefer that traffic control inside and outside the structure is during emergencies, what communication abilities they have and how it can be supported if they want and then how they can receive surveillance video feed, and how they want the collaboration to be during emergencies. If the fire department is well prepared and has structured parameters on what they can achieve and what they need to do, it can help the designer to find solutions in their favor.

5.3 Tactics and exercises

According to interviews, the modern tactics are well structured; in most cases, responding firefighters arrive from both ends of the tunnels, minimizing the duration from detection to first unit arrival by the effect of congestion on the route. By sending three units immediately as a first response towards the tunnel, to have one unit as a reserve for where it is needed, the time delay of calling out further resources is minimized. However, if information from the scene suggests that more resources are needed, the command centers dispatch more units. In the interviews, it was mentioned that it was already decided that the first two teams approach the fire scene through the smoke-free tube, where one has the task of supporting evacuation downstream and the other two approach the fire source from upstream for firefighting.

These tactics are similar to what is suggested in literature; however, theoretically, more significant scenarios can require extended resources for search and rescue in congested tunnels where larger vehicles are burning (Ingason et al., 2005). It can therefore be essential to send out even more units in the first phase if the scene is likely to develop further and involve larger vehicles.

The literature shows that fire development happens shortly, with the peak heat release rate in about the first 10 - 20 minutes. In contrast, the scenarios with higher heat release rates develop in a shorter time. Commonly, fire units are given 1 – 1,5 minutes after being dispatched to leave the station. The time to reach the tunnel portals varies; the fire stations are often located so that they can reach most city areas in 10 minutes, assuming that the BA-team prepares on the route and is ready for firefighting upon arrival. The time between the fire ignition and till BA-teams enter the tube under fire at the closest access point can be too long to reach the fire source before the peak heat release rate.

The fire department has some differences in how they prepare for tunnel incidents; however, there are more similarities with the fire department in the Nordic countries than differences. According to FF participants, training needs to be more frequent to prepare all personnel, reports of firefighting technics show how easily hiccups can occur during hose system layout and, therefore, time delay (Palm et al., 2016). To do BA operations far away from the next available exit point is stressful; firefighters should be familiar with tunnels in their area and their function. Infrared cameras were mentioned during interviews as essential for orientation in smoke-filled tunnels; in the literature, it is, however, mentioned that they are generally not adapted for tunnel environments and suggested that there should the development of both the equipment as well as the training material (Kumm et al., 2014). As suggested in the literature, the fire departments could try to minimize the time it takes to build up hose systems; a suggestion seen in the same literature is to have pre-coupled hoses in the fire trucks (Kumm et al., 2014); this is a common thing both in Iceland and Sweden.

As mentioned in the interviews some development has been tested regarding search and rescue tactics in metro tunnels (see section 4.2), tactics where BA-teams do not move hoses with them while searching for evacuees in distress have shown that there are possibilities to increase the movement speed for BA-teams located far away from the source of the fire. This is coherent with the rapport from Storm and Kumm (2023), where different search and rescue tactics in longer rail tunnels where tested to increase the efficiency of BA-teams. Possibly some of these tactics can be used for BA-teams downstream the fire source in road tunnels as well.

If possible, by shortening the time till the extinguishing starts, the peak heat release and heat flux can be minimized, therefore the safety of firefighters is raised.

Suggestions to shorten the time between fire ignition and the beginning of search and rescue or firefighting:

- Well trained proceedures, including all involved authorities so that all individuals know what their task is.
- Functioning equipment and good knowledge on its capabilities.
- Knowledge on intergraded equipment in tunnels and its capabilities.
- Well structured communications, firstly, between; incident commands, dispached centers and tunnel control centers, and secondly, between the responding firefighting units.
- Well structured emergency plans, including what to dispatch in first phase of operations, regarding traffic density in tunnels and possible involvement of larger vehicles.

5.4 Fire development and heat flux

In Swedish and Norwegian regulations, tunnels are divided into categories by AADT and tunnel length. The designed fire development is related to these categories; the difference is that in the Norwegian regulations, the ventilation and structure are to be designed for given fire development, but it seems that it is not used for other design parameters. However, in the Swedish regulations, tunnels that fall into categories TB and TA it is required to do risk analysis for possible fire development in the tunnel; by requiring risk analysis, the possible involvement of larger vehicles or vehicles transporting dangerous goods is insured. It is also interesting how the Swedish regulations include maximum criteria for tunnel environment during the evacuation phase. Where the firefighting tactics focus on the fire when the evacuation phase is over, the criteria after the evacuation phase could be related to the maximum heat flux for firefighters.

From interviews it seems that most tunnels are designed with larger HGV fires in mind, but that smaller fires including smaller passenger vehicles are more common. As an example for those of interest, theroretical values for gas temperature above the fire source and the heat flux are calculated according to Ingason et al. (2015) for 10 MW (commonly referred to when passenger vehicle burns) and 100 MW (commoly referred to when average HGV is burning, not carrying larger loads of liquid fuels) to show the difference in the tunnel environment for evacuees and firefighters.

When calculating maximum temperature in the ceiling above fires, where forced longitudinal ventilation (assumed to be 3 m/s) is in place, Ingason et al. (2015) reccommends the following equation:

$$\Delta T_{max} = \frac{\dot{Q}}{u_0 b_{fo}^{1/3} H_{ef}^{5/3}}$$ *Equation 1*

Where:
$\dot{Q}$ = Power output of the firesource [kW]
u_0 = Ventilation velocity [m/s]
b_{fo} = Radius of the fire source [m]
H_{ef} = Effective tunnel height [m]

As this comparison is only done for the purpose of better situational visualization, input values are roughly estimated.

If the fire source is assumed to be 1,5 m in radius for the 10 MW fire (smaller passenger vehicle) and 4 m in radius for the 100 MW fire (HGV) and the effective tunnel height (distance from the fire source to the tunnel ceiling) is assumed to be 5,5 m for the smaller fire and 4,8 m for the larger fire (Given that the tunnel is 6 m in height, the passenger vehicle fuel source is 0,5 m above the road surface and the HGV trailer about 1,2 m above).

$\Delta T_{max}(10MW) \approx 170$ K or °C

$\Delta T_{max}(100MW) \approx 1537\ K\ or\ °C$

As a part of the calculation the ΔT_{max} is given a maximum value og 1350 °C and therefore the $\Delta T_{max}(100MW)$ should be set to 1350 °C.

For calculating the heat flux at the ceiling for previously mentioned fire scenarios (10 MW and 100 MW) Ingason et al. (2015) recoomends using the following equations:

$$\dot{q}''_{inc,w} \approx \varepsilon_g \sigma T_g^4$$ *Equation 2*

Where:
$\dot{q}''_{inc,w}$ = Incident heat flux at the upper layer [kW/m^2]
ε_g = Gas emissivity (approaches 1 in larger tunnel)
σ = Stefan-Boltzman constant [5,67E-11 kW/m^{2}K^2]
T_g = Temperature of gas [K]

Assuming that ambient temperature is 10 °C and that ε_g = 1, where twin tube tunnels could be seen as larger tunnel.

$\dot{q}''_{inc,w}(10\ MW) \approx\ 2{,}5\ \mathrm{kW/m2}$

$\dot{q}''_{inc,w}(100\ MW) \approx 403\ \mathrm{kW/m2}$

The heat flux from the flame, affecting firefighters approaching the fire source in tunnels can be calculated. If it is assumed that forced ventilation is sufficient to prevent backlayering and therefore the heat flux from the upper layer is ignored. By following equations suggested by Haukur et al. (2015) and chosen input values from the previous used scenarios:

The heat flux toward the firefighter:

$$\dot{q}'' = \frac{\chi_r \dot{Q}}{4\pi R^2} cos\beta$$

Equation 3

Where:
$\dot{q}''$ = Heat flux received by firefighter [kW/m^2]
χ_r = The fraction of the total HRR that is lost by flame radiation (assumed to be 0,35)
$\dot{Q}$ = Heat release rate of the fire [kW]
R = Distance between the flame center and the firefighter [m] (assumed to be 20 m)
$cos\beta$ = The angel between the flame and the firefighter [°]

Calculated the theoretical heat flux towards a firefighter standing 20 m away, upstream the fire, assuming the maximum heat flux for when cosβ = 1, that the fire source and the fire fighther is located in the centerline of the tunnel and that the ventilation velocity is preventing backlayering:

$\dot{q}''(10\ MW) = 0{,}69\ kW/m^2$

$\dot{q}''(100\ MW) = 6{,}96\ kW/m^2$

As mentioned in the literature, for firefighters to deliver water to the fire source using standard equipment and regular water at 6 – 8 bars of pressure, the maximum distance is around 20 meters (Kumm et al., 2022) which is coherent with the theoretical calculations show above using suggested methods in Tunnel Fire Dynamics, written by Ingason et al. (2015). If theoretical calculations done by Ingason et al. (2005), shown in Figure 3, are used to find when BA-teams are unavailable to reach the fire source with water, it can be seen that 75 MW fires can reach close to the limit of BA-teams.

To involve the maximum allowed heat flux affecting firefighters as 5 kW/m^2 at 20 meters from the fire source in tunnel design could improve firefighters, safety and efficiency. Suppose the risk analysis suggests fire development for a new tunnel design that leads to a higher heat flux than the local fire department is confident with at a distance; they need to reach for firefighting with their equipment. Some counter measurements could be integrated into the design.

Possible counter measurements to lower possible fire development and therefore decrease heat flux on firefighters could be:

- Traffic restrictions or traffic control to lower the possible peak heat release rate. (See section below regarding traffic control)
- Ventilation, with suitable programming, can suppress, dilute and cool the smoke gasses and the fire source; however, it can also increase the fire growth rate in larger vehicles. (See section below regarding ventilation)
- Fixed Fire Fighting System (FFFS) with manual activation (See section below regarding extinguishing systems) and tunnel control center using an automatic detection surveillance system (See section below regarding detection and surveillance) to start early fire suppression, cooling the environment and slowing the fire development.

5.4.1 Concrete spalling

By analyzing what is possible and likely in each tunnel structure with risk analysis, the possibility of the correct base scenario for safety design is more likely. Though spalling will occur in case of high temperatures for a more extended period, the right choice of material and use of material with well-known properties could lower the risk of such incidents during firefighting operations.

5.5 Detection and surveillance

Some differences in chosen detection equipment can be seen from the interviews. The equipment mentioned included smoke detectors, cables detecting temperature changes, surveillance cameras, detection software, extinguisher removal detection, and detection for open emergency exits. Camera surveillance and automatic detection software were frequently mentioned and got a great review from the interview participants. Their confidence brings forward the thought that this could be the only detection equipment, assuming the installation and maintenance can have excellent resilience. The surveillance coverage would then need to cover the whole tunnel. As an additive, tunnel users can detect emergencies and alarm the emergency authorities with their cell phones if a cell phone signal in tunnels is in place. However, it is common knowledge that most individuals today carry cell phones. Another interesting installation in tunnels mentioned in the interviews is to have infrared cameras in place with all other cameras; their ability to identify evacuees when smoke starts to build up in the ceiling can help the incident commanders to distribute their resources as well as be used in automatic fire detection with the right software.

According to the interviews, the emergency activation time is reduced by using surveillance cameras with 100 % coverage and automatic detection software to alarm tunnel control center operatives. With such programs, one tunnel central can surveil multiple tunnels and operate their equipment; therefore, if a tunnel control central organization has been formed and is well functioning, new tunnels can be included in their surveillance with minimum cost. As also mentioned in the interviews, by using preprogrammed software to initiate the emergency phase and send an alarm to needed authorities, based on chosen location and incident type for operators, the possibility of human error and duration of emergency activation time is minimized. The operator then observes that everything is functioning correctly. And where software errors and failures exist, and in scenarios that have not been preplanned, the operatives can overite the software.

These factors increase the possibility of initiating evacuation, smoke ventilation, activation of FFFS, and traffic stop towards the tunnel on short notice. Therefore possibly lowering the probability of evacuees in distress and need of assistance from firefighters.

To increase the detection redundancy in case of, for example, a lost connection to all surveillance cameras, manually activated emergency buttons and emergency phones can be installed. However, a mobile individual with consciousness is needed to activate or use such equipment.

Some programs can register ADR vehicles automatically; knowing what dangerous goods are inside the tunnels when an emergency is detected can be helpful when deciding response tactics, amount, and type of resources. However, the problem with vehicles loaded with multiple smaller containers of all kinds of toxics and not in need of carrying ADR registration remains.

In none of the interviews, the thermal detection cables installed in many tunnels were mentioned as vital for detection. It is, therefore, a question if such equipment is needed.

As for other connected facilities not meant for traffic, participants mentioned that smoke detectors are being used, directly alarming the tunnel control centers or the fire departments when smoke builds up. As mentioned in the interviews, when the fire departments are immediately alarmed, the tunnel control centers are normally able to identify if there is a false alarm from technical rooms before the firefighting units have left their station. This function minimizes the time between the activation of the detector and the firefighting units arrival; however, if firefighters are frequently getting false alarms, their mindset regarding the possible intensity of the scenario ahead can be lowered. It is also interesting to evaluate if a fire in technical rooms is likely to develop into the same intense scenarios as fires in vehicles that stop the traffic flow inside the tunnels. And therefore, if that short response time is of the essence or if it is better to do as mentioned by some interviewees, allowing the tunnel control central to evaluate each alarm from technical rooms before alarming the fire departments.

5.6 Ventilation

When reading through the literature and interviewing experienced personnel in tunnel safety, it becomes clear that well-designed ventilation and how they are controlled are of the essence for safety in tunnels during emergencies.

Norwegian regulations require that the minimum velocity in smoke ventilation should be able to achieve 3 – 4,5 m/s for a 50 – 100 MW design fire. Swedish regulations and road traffic authorities guidelines mentioned that the minimum velocity is 3 m/s in tunnels longer than 1000 m, and for 100 MW design fire. The regulations also require that the ventilation is supposed to prevent backlayering and provide safety for evacuees and firefighters and mention that the ventilation fans closest to the fire can get damaged and, therefore, not functioning.

There is multiple research regarding how to control smoke ventilation in tunnels during an emergency. It seems, both from literature and interviews, that longitudinal ventilation with jet fans, ventilating in the traffic flow direction, is the most common setup in twin-tube road tunnels, designed to provide 1,5 – 4 m/s during an emergency. For longer tunnels, it was mentioned in the interviews as well as required, if needed, in the European regulations to have smoke extraction points distributed over the tunnel length. Suggested parameters to have in mind when designing longitudinal ventilation in twin-tube tunnels:

- Does selected equipment that withstand the expected temperature for the time needed for firefighting operations?
- Will the ventilation be able to fulfill its goals if one group of fans is damaged due to close proximity to the fire?
- Is there a tunnel control center that can operate the ventilation setting remotely
- Are the tunnel portals close to one another, will the ventilated smoke possibly move out of one portal and into the other portal and can chosen equipment prevent this?

According to the interviews, the ventilation velocity is commonly divided into two phases during emergencies. Were first phase is after incident detection until evacuation downstream is achieved, and the second phase, after evacuation downstream, is achieved till the fire has been extinguished. According to the literature, this would, however, need to be dependent on the type of scenario, and as mentioned in the literature, ventilation velocity can have different effects on different fires, increasing the fire growth rate in larger fires but slowing it in smaller fires as well as spillage fires. The interviews with firefighting experience did emphasize firefighting from upstream with the wind in their back, as is in accordance with the literature, but as also mentioned in the literature, if the tunnels are congested, too strong ventilation velocity can affect the evacuation process, and therefore, possibly more BA-teams would be needed for assistance.

In the first phase, the literature suggested for none congested twin-tube tunnels that, the ventilation velocity is set to be just enough to withstand backlayering, therefore supporting evacuation by foot upstream and forcing smoke downstream faster than needed. However, in congested tunnels, this can increase the risk for individuals stuck in traffic downstream. Experienced personnel in tunnel management mentioned that when their system detects stopped traffic or individuals outside their cars, their procedure is to significantly slow down the ventilation velocity until they have either confirmed fire or toxic leakage or analyzed the reason for the abnormality in traffic flow better. Personnel within the same profession mentioned that the ventilation is set directly to 3 m/s and another 4 m/s after confirmation of a fire in their tunnels. It is worth to mention that in the case where the ventilation velocity is set to 3 m/s, the tunnels are equipped with FFFS, and this was decided with support from their experience and tests.

Ventilation velocity of 3 m/s is in accordance to what the literature suggest for the case of no queue formed downstream in, a multiple lane, unidirectional road tunnels to prevent backlayering, but not in accordance with what is suggested for congested tunnels. Where needed ventilation for preventing back layering might worsen safety compared to minimal ventilation since it raises the fire growth rate and forces smoke toward evacuees downstream. The suggested velocity in case of a formed queue downstream, to reduce the risk for fire spread to nearby vehicles and improve initial conditions during evacuation is mentioned to be 1,5 – 2 m/s, as for when the evacuation is finished and at the stage of firefighting it is suggested to increase the velocity to a slightly greater level than the critical velocity or to 3 – 3,3 m/s (Li & Ingason, 2016).

For when it is chosen to include FFFS in tunnels, research has shown that higher ventilation has a potential to compete with the suppression systems, tests have however shown limited influence from ventilation on the extinguishing abilities of FFFS with a side spray nozzle and a water density of 10 mm/min in the velocity range of 1,5 – 3 m/s. It is therefore recommended to use the ventilation velocity of 3 m/s for when FFFS are included (Li & Ingason, 2016).

According to experienced personnel both in firefighting and tunnel management, the ventilation velocity procedures are similar for scenarios involving fire and for when there is a leakage of dangerous chemicals. Where it is thought best to dilute leaking or evaporated gases for spillage fires, higher ventilation is also mentioned to have a positive influence in the literature, by suppressing the fire development in spill fires.

As mentioned in the literature, and as experienced firefighters mentioned in the interviews, ventilated smoke can and has moved between tubes by their portals. In most cases, the countermeasure seems to be reversing the ventilation direction in the smoke-free tube to ventilate both tubes in the same direction.

The procedures for smoke ventilation during emergencies could be separated into more groups; with automatic surveillance video analysis, it could still be possible to allow for an automatic choice of some settings, but due to multiple parameters involved in what type of scenario is in place, the intervention of well-trained tunnel control operators could be the safest option. Suggested parameters to have in mind when choosing different ventilation settings in the first phase could be:

- Is there a confirmed fire or dangerous chemicals leaking?

- Are vehicles involved in the fire development, are vehicles close enough to ignite, or is there a spillage fire with no vehicles around?
- What type of vehicles will be allowed in the tunnels?
- Will there be traffic congestions downstream, upstream, or both?
- Is there a need to prevent smoke from moving between portals?
- Is it possible to support laminated smoke flow?

And for when an evacuation has finished downstream, suggestions of parameters to have in mind when choosing ventilation settings for the second phase could be:

- Firefighting tactics involve entering the tube under fire from the next available access point upstream of the source to approach with the wind in their back.
- Firefighters efficiency increases with lower heat flux and better visibility
- Firefighters in standard protective gear, wearing BA, are not protected against toxic intake through their skin.

5.7 Emergency exit/access, water access and dry pipes

There is available literature suggesting equations to speculate the needed water flow for extinguishing different sizes of fires. However, there has been a fast development in vehicles in the last decade. The training level between fire departments differs, as well as their availability of equipment. With the fire departments involvement in tunnel design, their suggestions and experience on needed water flow for the scenarios the tunnel design is based on can be collected. The amount of needed flow could be built on experience from previous car fire incident reports, where it depends on what type of tactics are being used. During the interviews with experienced firefighting personnel, it became clear that water access points in tunnels are being used. According to the literature, for when firefighting larger fires, there is a need for more water than the standard firetrucks carry. And as also mentioned in the literature, larger fire scenarios require multiple resources; therefore, if there is no water access in tunnels, even more resources are needed to transport water. In the interviews, dry pipes were frequently mentioned as a good possibility to guide water flow between tubes without risking smoke moving between tubes. An interesting setup was mentioned, where the water access connections or hydrants are colored blue and dry pipes connections are colored red for easy identification of each connection purpose.

It could therefore be good for tunnel designers to have in mind the following bullet points, therefore possibly minimize the time and resources it takes to get water access and to get pressurized water to the tube under fire are:

- Locate water access points beside each emergency access between tubes.
- Design the water system size and pressure to ensure the needed water flow to firefight the chosen design scenarios.

- Locate dry pipes between tubes, where connections are located beside the water access connection.
- Have connections with different purposes in a different color, preferably colors that the fire department can relate to.
- To use the same couplings on connections as the fire department is familiar with.

By conducting interviews with experienced firefighters and by reading through the literature, it becomes clear that the distance between emergency exits or access points, when referring to firefighting operations, is of the essence. Were shorter distances increase their safety and efficiency, allowing the BA-teams to have longer working duration inside the tube under fire. Therefore, more time for search and rescue or firefighting and a quick exit in case of a sudden change in the scenario.

As shown in the analysis done by Palm et al. (2022) the travelling distance is limited by the BA-teams air capacity. When fire department aims to use standard 6 liter air system, the maximum distance between emergency access is about 75 meters (Palm et al., 2022). It is therefore neccesary to include the capabilities of the local fire department for when assuming the distance between access points in case it is shorter than what is needed for safe user evacuation.

While the European regulations require tunnels to be built so that they provide rescue services with good possibilities to achieve their tasks, the Swedish regulations seem to be more specific, mentioning that the BA-teams safety can be the determining factor for distances between emergency exits. The Swedish regulations also mention that if the distance is longer than 200 meters between emergency exits in a tunnel longer than 300 meters, criteria regarding sight, heat flux, and temperature in the environment need to be met during evacuation.

If the evacuation time can be minimized, the firefighting could be executed earlier and with more resources than if BA-teams need to be supporting the evacuation process.

To find out if the distance between access points is sufficient, worst-case scenarios can be set up regarding the distance needed to be traveled.

A suggestion for a worst-case scenario could involve a fire at one access point and preventing it from being used. Assuming that the tactics mentioned during interviews and suggested in the literature are used (see sections above regarding tactics and exercises) and longitudinal ventilation, preventing backlayering.

Maximum distance between access points could be assumed by including parameters related to their tactics. Those parameters can be different between fire departments, depending on their training level and equipment. The local fire department could therefore supply designers with what they are confident of achieving regarding moving speed in a smoke-free environment (upstream) while building up hose systems simultaneously, moving speed without hose for when BA-teams retrieving or other BA-teams come for support and the working duration for BA-teams. The time needed to travel over the worst-case distance and build up the hose system towards the fire source, along with the time needed to retrieve the same distance, can be subtracted from the available time BA-team has. If the time available for firefighting is thought to be sufficient for the extinguishment of the designed scenario and the needed BA-teams to perform the task are available by the local fire department, the distance could be sufficient. However, this scenario assumes that the evacuation process is finished and, therefore, focuses on the needed distance to extinguish the fire, not including search and rescue operations.

When choosing the distance between emergency exits, the following bullet points regarding common firefighting tactics can be evaluated:

- The maximum distance to travel for firefighters is the same as the distance between emergency exits.
- If the used distance between emergency exits suggests that evacuation can be over before the arrival of the first responding firefighting unit, more resources can be used to firefight.
- Moving speed for BA-teams with water-filled hoses and building up hose system in a smoke-free tunnel environment has been measured at about 0,3 m/s and 1,3 m/s when BA-teams are not moving hoses with them (Bergqvist, 2001).
- Moving speed for BA-teams with water-filled hoses in a smoke-filled tunnel environment is assumed to be around 0,1 – 0,2 m/s (Ingason et al., 2005).

5.8 Extinguishing systems

As shown in the literature, fires in multiple vehicles, single heavy goods vehicles, or vehicles transporting dangerous goods can form fire developments that can be difficult or even impossible to approach close enough to extinguish with standard firefighting equipment. It is, therefore, a question of what to do when possible design fire development involves too high heat flux for firefighters to be able to approach the fire. As mentioned by Swedish participants in the interviews, the latest tunnel structures that have involved risk for congestion or allow the transport of dangerous goods are equipped with FFFS. Those that have experienced its function emphasize the systems availability to suppress fire development and, therefore, lower the heat flux; this is in accordance with the literature. It might therefore be a good solution to follow the path of newer Swedish tunnels and install fixed firefighting systems when tunnels are prone to congestion or allow traffic of vehicles that singularly can form such fire development. It is however important to choose the ventilation velocity in relation to the use of FFFS and rely on researches. Li and Ingason (2016) concluded, after their analysis on the influences of ventilation in road tunnel fires with or without water-based suppression systems, that the ventilation velocity should be around 3 m/s when FFFS are involved (see section 5.6).

An example of the benefits of using FFFS, like used in newer Swedish twin-tube tunnels, is mentioned in the report Large scale fire test with fixed firefighting system in Runehamar tunnel, written by Ingason et al. (2014), authors mention:

> The benefits of FFFS are primarily that they can be used to increase safety in tunnels. Such systems will be able to fight fires that are relatively large and thereby potentially prevent a major disaster. In the case of congestion, and specifically when a queue is formed, the system will increase safety by minimizing the risk of propagation of a fire as it could occur. (Ingason et al., 2014)

The result from the previously mentioned test indicates that a design fire of 100 MW can be reduced to half or 50 MW with the presence of such a system, lowering the risk of construction and equipment damages, meaning shorter downtime and repair cost; lower heat flux against evacuees and firefighters, lower probability of ignition in nearby vehicles (Ingason et al., 2014). The installation would, therefore, likely increase the possibility for the fire departments to successfully extinguish the fire with minimum casualties or damages to the structure. Some difference is in the type of chosen system according to the literature; mechanical or automatic activation, high-pressure fog, long-throwing side sprinklers in the center of the ceiling, or standard ceiling sprinklers distributed over the ceiling.

It is also worth mentioning that multiple other research is available regarding the benefits of different FFFS and how they can possibly involve expense savings in other design parameters.

5.9 Communications

According to the interviews, tunnel control centers are in place in all of the larger countries that participated. There seems to be good and clear communication in most places, and that is thought to be of the essence, both by experienced individuals within the fire departments and within the tunnel management. This is in accordance with suggestions from the literature.

By reading through the literature and analyzing the interviews, a list of suggested information that can help incident commanders to make the right decisions at the beginning of their operations has been formed. Suggested information that can be gained by the traffic control center at the beginning of operations to support the efficiency and safety of responding units:

- Location of tunnel.
- What tube is involved, and what tube to use for access.
- Status of traffic closure and access availability.
- Location inside the tunnels (See the section below regarding tunnel signals and lightning).
- Type of fire source,
- How many vehicles are involved.
- If vehicle extrication is thought to be needed.

- Density of traffic downstream and upstream.
- Heavy goods vehicles nearby (if ADR plates are visible, is it possible to identify the type).
- Status of evacuation.
- Ventilation settings (if installed).
- Status on FFFS (if installed).

It is required by European regulations that radio re-broadcasting equipment for emergency services is to be installed in tunnels longer than 1000 meters with traffic volume higher than 2000 vehicles per lane. Swedish regulations also require the same equipment for tunnels of 300 - 1000 meters if the signal is insufficient. Both experienced individuals within the fire departments and the literature mention that good communication availability is of the essence for rescue operations and firefighters safety.

5.10 Drainage systems

By designing and installing a drainage system that minimizes the possibility of flammable or toxic spillages on the road, the risks for fast growth spill fires could be minimized, as well as the possible contact with tunnel users and firefighters. As required by European regulations, drainage systems have to be designed so that fire or toxic fumes do not spread further in the tunnels where the transport of dangerous chemicals is allowed. The distance and location of drainage points could also affect the availability of evacuation routes and, as well as, the available access points for the fire department. For tunnels allowing the transport of dangerous goods in Sweden, regulations provide stricter requirements on drainage systems. Requiring that each drainage point serves a maximum of 200 m^2 and that the maximum distance between drainage points is 20 meters, the capacity of every two drainage points of the system is also required to allow 10 m^3 of liquid (with properties of water at 10 °C) released simultaneously to disappear from the surface in two minutes.

By following a similar setup, the probability of spillage fires could therefore be lowered, where most of the leaked liquid likely disappears before it burns. If it leaks slower and ignites, it could, however, burn at the same rate as the leakages flow and even catch on the tank of the vehicle.

It is worth mentioning that if FFFS is installed, designed FFFS water flow could affect the drainage system capacity during its activation.

5.11 Traffic control

As suggested in the literature and by analyzing interviews, practiced procedures during emergencies in tunnels involve traffic being stopped towards both tunnel tubes and opening barriers to allow arrived fire units to move between tunnel portals before entering; this is done remotely by the tunnel control centers. When traffic density towards the tunnels is high, congestions build up outside the tunnels. That can affect the arrival time of responding units, and according to experienced individuals within tunnel management, it is difficult to solve. Possibly, Traffic engineers can find solutions for such problems if they are involved in emergency plans.

According to the literature, congestions inside tunnels increase the risk of evacuees on foot downstream of the fire; it affects the possibility of forcing the smoke downstream in favor of evacuees forced to evacuate by foot, upstream, and BA-teams. If the smoke reaches evacuees downstream, the probability of the need for assistance from the fire department could be increased. The task of search and rescue can be resource-consuming, and therefore, fewer BA-teams would be available to assist upstream or to approach the fire. Therefore it could lower the risk of such scenarios by analyzing the traffic flow around new tunnel structures early in the design phase and involving needed authorities to find the best possible solutions on how to support evacuation with vehicles downstream of the fire. The same solutions could then possibly help to evacuate the tube that is supposed to be used for firefighting units when approaching the scene and therefore possibly shortening any delays on their arrival.

Some experienced individuals in tunnel management thought that opening for traffic evacuating from tunnels could impact the nearby city traffic network too harshly. Then according to the interviews, the need for such intervention seems to be unfrequent. The questions are if such intervention in the nearby city traffic network can save lives, increase the safety and efficiency of firefighters, lower the risk for longer closure of the tunnels due to damages, and how long time such interventions would need to make a positive difference. When these questions have been answered, the advantages can be compared to the disadvantages.

As some interviewees mentioned, traffic control outside tunnels is controlled by some tunnel control centers, then with the purpose of clearing the path for responding vehicles to minimize their travel distance and allowing their vehicles to pass by stopped traffic.

Parameters for designers to keep in mind when designing for traffic around and inside tunnels during an emergency could involve:

- Possibility to stopp all traffic towards the tunnel portals, and if barriers further away will decrease possible firefighting units arrival delay from congestions.
- Can the evacuating traffic be supported with traffic control in the nearby traffic network.
- For longer tunnels, can the traffic upstream be guided out of the tunnels through other openings.

5.12 Tunnel signals and lightning

As mentioned during the interviews, difficulties in identifying which tunnel tube was suggested to use to enter the tunnels can lead to delays in operations. By using well-visible signals with the same marking as the tunnel control central uses to identify them should be outside each portal; these signals could identify each tube with an easily identifiable difference and be referred to when the response units are dispatched. Each emergency access could be identified with a signal standing out from the tunnel wall with an angle so it is easily identified for arriving response vehicles, regardless of the direction they come from; these signals could have simple labels for identification and be used when tunnel control central locates the depth of the incident source.

To further increase the visibility of the access point closest to the scene, the setup mentioned by one experienced tunnel management individual, where the tunnel control central can illuminate chosen access point in the smoke-free tube.

5.13 Other equipment

The EU directives regulations require a network of electric power outlets to be installed along the tunnels for the fire department to power their tools; according to an experienced individual in tunnel management with such installations in his tunnel, these electric power outlets are never used. Modern tool setups on fire trucks commonly include battery-powered tools and backup batteries charged from the truck generator. It may, however, be needed in coming years to connect electric firetrucks to sufficient outlets to charge their main batteries, depending on when or if the fire department is equipped with electric vehicles. Where this is an unknown factor, and if they need to be charged during operations, it may be better to install such power outlets when these factors are known.

5.14 Regulations

As mentioned earlier in this rapport, the Nordic countries are to fulfill the minimum requirements of the European Union, directive 2004/54/EC for all road tunnels connected to the European road network. Norway and Sweden have also applied separated regulations, in force for all of their tunnels. When comparing the European Union minimum regulations together with the Norwegian N500 and Swedish regulations TRVINFRA-00233 (see Table 2), as shown in Table 2 the Swedish regulations seem to be more thorough and give in most cases more detailed guidelines for the designer on how to approach increased safety. The Swedish regulations and guidelines consider the safety and efficiency of firefighters more frequently as well as using risk analysis more often to figure out the needed mitigations.

Possible improvements in regulations could include:

1. The maximum criteria firefighters are thought to withstand without increased risk compaired to their most common firefighting operations, their safety would be increased. The maximum criteria is however related to the local fire department training and type of protection gear and would therefore need to be related to local fire department capabilitites.
    a. To fulfill this requirement, when the design fire development is thought to provite heat flux above the local firefighters limit at the beginning of their operations, the structure would need to be designed to withstand the high temperatures untill the fire development degreases or include some mitigation to minimize the fire development.

    b. If the design fire requires more response capacity than the local fire department has available as first response, the tunnels could be required to have some mitigation like FFFS, transport restrictions, traffic control towards the tunnels or that the local fire department capacities are increased.
    c. If users are thought to be likely to need assistance of the fire department during evacuation, the fire departments capacity to firefight is reduced. By including factors affecting the resources of the fire department, in regulations or guidelines, tunnel owners and designer will be guided to have some knowledge of the local fire departments capabilities.
2. Distances between emergency exits and fire hydrants seem to commonly be shorter than some regulations require, and shorter distances both said to be for better efficiency and safety, according to interviewees as well as seen to give advantage in literature. By shortening the maximum distance between emergency exits to what is practiced, including hydrants and dry pipes at every exit, the needed time and resources to build up hose system, as well as the distance BA-teams need to travel could be aimed to increase firefighters efficiency and safety.
3. By require specific waterflow at hydrants that is related to the design fire development at the time the fire department is thought to begin their operations, the extinguishing possibilities are strengthened as well as the firefighters safety and efficiency would be increased.

6 Conclusions

This report set out to evaluate how firefighting tactics in twin-tube road traffic tunnels can be made safer and more efficient through infrastructure design and installed equipment. To achieve this objective, a literature study was conducted and individuals in the Nordic countries with experience in the field were interviewed. Knowledge of hazards, challenges, firefighting tactics, firefighters limits, tunnel management procedures, tunnel design, emergency equipment in tunnels, experience, modern practices, viewpoints, and opinions were gathered.

All gathered knowledge was analysed, the report identifies the parameters that affect firefighter safety and efficiency during twin-tube tunnel operations, and brings forward suggestions for solutions.

In the discussion chapter, suggestions on how to include different parameters that affect firefighting tactics in the design phase to evaluate if the design provides an opportunity to perform rescue operations, therefore providing valuable insights into the opportunity to increase firefighters safety and efficiency. By doing so, the consequences in case of emergencies might be lowered.

The results of the study show the importance of:

- Collaboration between designers, tunnel management, and fire departments during the design phase.

- Well-trained firefighters and tunnel control center operators.
- Well-structured communications between responding units and tunnel control centers.
- High-quality surveillance system with automatic detection software covering the whole tunnel link.
- Well-designed access point setup, with access to water and the availability to get pressurized water between tubes.
- Well-designed ventilation systems and the right procedures for ventilation during emergencies.
- Fixed firefighting systems in case of larger fire developments that are beyond the limits of firefighters to approach.
- Well-designed drainage systems in case of transport of dangerous goods.
- Analysing the traffic flow inside the tunnels, towards the tunnels, and afterward the tunnel to find the best solutions regarding tunnel evacuation and routes for responding vehicles.
- The importance of importing firefighters limits in regulations and detailed guidelines on how to support their safety and efficency during tunnel emergencies.

Overall, this report provides valuable insights into the opportunity to increase firefighters safety and efficiency in twin-tube tunnels, with the potential to minimize the consequences of emergencies.

6.1 Future studies

While this report provided suggestions on how to involve firefighting when designing tunnels, there is still more that can be studied. Further, some potential areas for further research include:

- To analyze the minimum section length of FFFS to achieve needed fire suppression, shorter sections and less water flow in FFFS could lead to less impact on both drainage system designs and water flow in the supply system for firefighting.
- Research of higher ventilation velocity with activated FFFS, regarding the benefits of more diluted toxins, cooled-down environment, and flames leaning away upstream traffic, against disadvantages of faster fire growth and effect on evacuees or vehicles downstream, the result from such research could lead to different ventilation strategies for ventilation with FFFS. This could then be researched for both high or low-pressure fixed firefighting systems.
- The possibility to use software to analyze the traffic density inside and outside tunnels, with the aim to automatically use different first-phase procedures regarding ventilation velocity and, therefor, support evacuating traffic downstream when needed, like during rush hours.

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Appendix 1

The following appendix shows the base questions for the interviews aimed at participants with incident firefighting commanding experience.

1. What is your education and/or experience in tunnel firefighting/design/management?
2. Do you recall many incidents in tunnels in your area?
3. Do you think there is a need for improvement related to firefighters safety in tunnels and how their efficiency is supported?
4. Strategies and procedures
   - 4.1. What tactics or strategies do you aim to use when responding to tunnel-related incidents?
   - 4.2. Do you have different equipment for such alarms than house fires?
   - 4.3. If your team experiences any failure in the tunnel structure on their way in, would they proceed or fall back?
   - 4.4. Are there any special procedures in case of a hazardous chemical leakage involvement other than on an open road?
   - 4.5. What is the procedure for a tunnel-related emergency call to the call center?
   - 4.6. What information do you prefer to receive on route?
   - 4.7. Does your department use different methods when pre-planning tunnel firefighting than f.ex a house fire?
   - 4.8. What methods do you aim to use: Foam, water, CAFS?
   - 4.9. Why do you use those methods?
5. Is your fire department involved in the design of tunnels in your area?
   - 5.1. How are they included?
   - 5.2. Do you train for tunnel incidents?
   - 5.3. How often?
   - 5.4. What setup do you use for training?
   - 5.5. How do you collaborate with tunnel owners, management, or designer when training?
   - 5.6. How do you collaborate with the tunnel owners or designers when pre-planning?
6. Fire department equipment and experience
   - 6.1. What data is available for the incident commander at arrival?
   - 6.2. Is it possible to access surveillance cameras and the values of sensors?
   - 6.3. Are there any layouts of the tunnels and their systems available?
   - 6.4. What type of communication do you use for firefighters using SCBA?
   - 6.5. How is the signal between radios in tunnels in your area?
   - 6.6. Is there a signal booster?
   - 6.7. Do you use the same air tanks as in-house firefighting, larger tanks, or OBA equipment?
   - 6.8. Do you use thermal cameras while entering tunnels?

6.9. How easy is finding the incident source when it is not visible from the portals?

7. Is there any design measurement you suggest to make it easier?
8. For a car fire, do you assume to use regular water hoses, specified foam reels, or high-pressure reels when engaging?
9. What is your opinion regarding design measurements or on-site equipment that supports effective tunnel firefighting?
10. Overall opinion?
11. If there is a water reservoir for firefighting, who inspects it, and how often is it done? Does it work fluently when used?
12. How does your department prefer that the ventilation is controlled during incidents?
13. Pre-arrival and after-arrival?
14. On what ground are those decisions made?
15. Have you experienced smoke moving between portals in twin-tube tunnels (one tunnel venting out and the other dragging smoke in) while it is being ventilated, and if so, has it worsened the conditions?
16. Can you manually control the onsite equipment, and is it easily understood how to do so?
17. Are the technical rooms to access control easily assessable?
18. How do you know if people are still evacuating on arrival, and if so, does it change your strategies?
19. Are there any registered incidents regarding personnel during tunnel firefighting, and are they available for my project?
20. Is there any other thing that you can think of related to the matter that you would like to mention?

Traffic control

21. What is your experience regarding traffic control towards the tunnels during incidents? How and in what way is it working for your teams when they are on their route and close to the portals?
22. Does it have a considerable effect on your arrival time?
23. Who controls the traffic near portals during incidents?
24. How does the collaboration regarding traffic control function between incident command and other needed authorities during emergencies?
25. How is the traffic flow controlled?
26. What are the goals of your traffic control, for example, keeping up the flow or clearing the path for rescue vehicles?
27. Who makes the decisions, and on what grounds?
28. Is there any automatic collision detection in the tunnels in your area?
29. Who gets alarmed?
30. Is any turnaround available outside or inside the tunnel, and how important are they?
31. Tunnel equipment

Detection

32. Is any surveillance equipment available for the command control, such as sensors or cameras?
33. Is it used during incidents?
34. How is it used, and what for?
35. Are the cameras in the ceiling or wall mounted below the ceiling?
36. Are the cameras usable when there is smoke building up?
37. Is there any automatic alarm, and who gets the alarm signal?
38. What type of detection?
39. Why was that type of equipment chosen?
40. Do you get any false alarms from these automatic systems?

Ventilation

41. Is there a mechanical ventilation system?
42. What type of ventilation?
43. Who controls the ventilation, and how is it controlled?
44. Who decides how they are operated during incidents, and on what grounds are those decisions made?
45. How is the procedure regarding ventilation control during a fire or toxic leakage?
46. Could on scene supervisor overtake the control or get directions/power changed quickly?

Chemicals

47. Is there a hazardous chemical liquid drainage system?
48. Is there any limit on transporting hazardous chemicals through tunnels in your area?
49. Is there any possibility of identifying what type of chemical is inside the tunnels during incidents, f.ex. With a surveillance system?

Emergency exits/entries

50. How far is between emergency exits/entries?
51. Do you think that the distances used are sufficient?
52. Do emergency exit doors have spy holes, and are they used during incidents?
53. Are there any markings to show what emergency exit/entrance is closest to the scene for the fire department?
54. Do you think such markings would help find the source?

Water supplies

55. Is there a sprinkler system?
56. Do you know what type of a system?

57. How is it activated?
58. Does it activate in the whole length of the tunnels, or is it sections based?
59. Are there hydrants available inside the tunnels for the fire department?
60. How far distance is between hydrants?
61. Are the hydrants located close to emergency exits/entries?
62. Do you think it helps to have the hydrants located so that there is a minimum of work needed to apply water to the fire truck and from there to the emergency exits/entries?
63. Are there water pipes between parallel tunnels to allow water to flow between without keeping exit/entrance doors open?
64. If so, do you use them or take the hose through the emergency exit/entry doors?
65. If you planned to use foam, are you equipped to connect the foam through such “between pipe”?
66. Would it help to have the emergency exit/entry doors equipped with a flap on the lower edge to close the door with the hose through?

Other

67. Are plan boxes accessible on-site?
68. Do you think that they are used and useful?
69. Is there any equipment to support communications for firefighters inside the tunnels?
70. Have any upgrades in older tunnels improved firefighting efficiency?

Appendix 2

The following appendix shows the base questions for the interview aimed at participants with experience in tunnel management or design.

1. What is your education and/or experience in tunnel firefighting/design/management?
2. Do you recall many incidents in tunnels in your area?
3. Do you think there is a need for improvement related to firefighters safety in tunnels and how their efficiency is supported?
4. What is your procedure when a tunnel-related emergency call is made to the emergency call center?
5. Do you collaborate with the tunnel designers or fire department when making pre-planning documents?
6. Does your staff have some special pre-planned procedures in case of incidents, like traffic control, manually activating sprinklers, manually controlling ventilation, identifying the source, or seeking better information for the fire department?
7. Are there any special procedures in case of a hazardous chemical leakage involvement?
8. Do you use camera recordings to identify the chemical transportation for better information?
9. What is your opinion regarding design measurements or on-site equipment that supports effective tunnel firefighting?
10. If there is a water reservoir for firefighting, who inspects it, and how often is it done? Does it work fluently?
11. How does your company prefer that the ventilation is controlled during incidents?
12. Have you experienced smoke moving between portals while it is being ventilated, and has It worsened the conditions?
13. What is your experience regarding traffic control towards the tunnels during incidents?
14. Are there any incident or exercise reports available from your company?
15. Are there any registered incidents regarding personnel during tunnel firefighting? Had it been possible to avoid it, and if so, how?
16. Is there any other thing that you can think of related to the matter that you would like to mention?

Traffic control

17. Who controls the traffic near portals during incidents?
18. How do the incident command and other needed authorities collaborate during emergencies?
19. How is it controlled?
20. What are your traffic control goals, keeping up the flow or clearing the path for rescue vehicles?
21. Who makes the decisions, and on what grounds?
22. Is there any automatic collision detection in the tunnels in your area?
23. Who gets alarmed?

24. Is any turnaround available outside or inside the tunnel, and how important are they?
25. Tunnel equipment

Detection

26. Is any surveillance equipment available for the command control, such as sensors or cameras?
27. Is it used during incidents?
28. How is it used, and what for?
29. Are the cameras in the ceiling or wall mounted below the ceiling?
30. Are the cameras usable when there is smoke building up?
31. What do you use to surveil the scene if the cameras are unusable?
32. Is there any other type of detection that you would like to mention?
33. Is there any automatic alarm system, and what type?
34. Who gets the alarm signal?
35. What is the procedure for when the system is activated automatically?
36. What type of detection?
    36.1. Why was that chosen?
37. Do you get false alarms?
38. How do you minimize false alarms?
    38.1. Do you have alarms for when emergency doors are opened or extinguishers are removed?
39. Are that information passed to the incident command, and if so, how?

Ventilation

40. Is there a mechanical ventilation system?
41. What type of ventilation?
42. On what ground are those decisions made?
43. Who controls the ventilation, and how is it controlled?
44. Who decides how they are operated on during incidents?
45. On what ground are those decisions made?
46. How is the procedure regarding ventilation control during a fire or toxic leakage?
47. Could on scene supervisor overtake the control or get directions/power changed quickly?

Chemicals

48. Is there a hazardous chemical liquid drainage system?
49. Is there any limit on the transport of hazardous chemicals?
50. Is there any possibility of identifying what type of chemical is inside the tunnels during incidents, f.ex. With a surveillance system?
51. Emergency exits/entries.

52. How far is between emergency exits/entries?
53. Do emergency exit doors have spy holes?
54. Is there any light or markings that show what emergency exit/entrance is closest to the scene for the fire department?
55. If yes, how do you activate them?
56. Is the locations or their existence known to the fire department?
57. If not, do you think that it would help?

Water supplies

58. Is there a sprinkler system?
59. Do you know what type of a system?
60. How and when is it activated/controlled?
61. Does it activate in the whole length of the tunnels, or is it sections based?
62. Are there hydrants available inside the tunnels for the fire department?
63. How long distance is between hydrants?
64. Are the hydrants located close to emergency exits/entries?
65. Are there water pipes between parallel tunnels to allow water to flow between without keeping the exit/entrance open?

Other

66. Are plan boxes accessible?
67. Do you think that they are used and useful?
68. Is there any equipment to support communications for firefighters inside the tunnels?
69. Have any upgrades in your tunnels improved firefighting efficiency over the years?

Appendix 3

The following appendix is a short version of nine interviews concerning this project. All information that jeopardizes the animosity has been cleared out.

Interview 1

The interviewee has over a decade of working in fire emergency response to tunnels on behalf of a fire department and answered multiple callouts to minor fire incidents in their road tunnels. At this time, the interviewee has never experienced an injured collage after a tunnel-related operation. Most of their callouts are related to traffic incidents or automatic fire alarms in the technical rooms located inside the tunnels. There has never been a significant incident in their tunnels.

The interviewee thinks that newer road tunnels in their area are being built safely and providing excellent possibilities for the fire department to achieve its goals. Their department has approach plans for each tunnel, including what amount and type of resources should be called to the scene. Each unit called out gets its task and location through the radio. They always approach from the unaffected tube and use the emergency exits to move between tubes close to the incident source.

The participants fire department is always involved in new tunnel designs, most often in the early stage. A good dialog is between the fire department, the owners, and the designers. Often they can fulfill even safer tunnels than the countries requirements require.

The fire department has one joint road tunnel exercise annually with the police, ambulance services, and the tunnel operation center. They have major practical exercises every third year and for each new tunnel. All exercises are performed with cold smoke.

They approach all fires and chemical leaks similarly, regardless of their scene size or type.

Their department does not have special equipment for tunnel incidents and aims to keep it that way.

If they would experience failure in the tunnel structure, it would be reported to the chief commander, and a joint assessment and risk assessment would be carried out for other decisions, which can lead to quite a delay.

When something is abnormal in their tunnels, the tunnel traffic central is alarmed instantly by automatic surveillance camera detection; they then alarm the emergency center, which alarms the fire department. If the tunnel SOS phones are used, the traffic control center answers and alarms the emergency center. Suppose an individual call the emergency center by cell phone. In that case, the emergency center alarms the fire department and the tunnel control center, and they can then confirm and locate with their surveillance system.

Critical information for the fire department en route is which tube is involved, what type of incident, if the tube has been closed, and what emergency exit/access is closest to the incident source.

Their fire trucks are equipped with portable computers, allowing the units commander to review the emergency plan en route.

Their fire trucks are equipped with normal pressured water, semi-high pressured water, CAFS system, and Cobra system. However, they most commonly choose the normal pressured water as their extinguishing method.

When arriving at the tunnel portal, the incident commander has access to an operating room with a good overview of the tunnels and screens that the tunnel center can share camera views on, a direct phone to the tunnel central, which fire alarms are activated, and the current wind velocity in the tubes.

The tunnels in their area are well covered with surveillance cameras; by them, the tunnel control center can identify and locate the source of the incident and follow the evacuation process. They will also ensure no traffic in the smoke-free tube before opening the gate, allowing the fire department to drive against the traffic flow. Their surveillance system is, however, not powerful enough to identify ADR plates on vehicles with dangerous goods.

In most of their tunnels, signal-booster equipment is installed to support their communications, and in all of them, there are overpasses outside each portal to move between tubes. All of their tunnels are supplied with water from the municipal water network, with a connection at every emergency exit and a dry pipe between the tubes; the distance between emergency exits is most often every 100 – 150 m. The interviewee mentioned that they are satisfied with the distances between emergency exits, the dry pipe solution, and hydrant locations. About two sections of temperature measurement cables are installed in the ceiling between every emergency exit; a sudden temperature rise and a maximum value are used to notify the tunnel control center of a possible fire.

All their tunnels are equipped with impulse or ordinary fans, providing longitudinal ventilation; the ventilation is automatically started at fire alarms. The incident commander can then ask the tunnel control center to change the settings for the ventilation; for some years, they were able to adjust the settings on-scena but have concluded that it is more efficient to refer to the tunnel control center.

If there is a confirmed fire or a gas leakage, the system starts automatically in both tubes and keeps the velocity between about 1,5 m/s in the traffic flow direction of the tube under fire. There have been tests to pull out the smoke rather than pushing it to minimize the turbulence inside the tube. Upon the fire departments arrival, the incident commander decides if the ventilation needs to be adjusted; however, they usually do not increase it a lot but try to maintain it at 1,5 – 2 m/s. There have been tests to see what ventilation velocity is preferred. Their results support those settings even though the evacuation has finished; these settings minimize the smoke spread upstream and do not drive it downstream too fast. After extinguishing the fire, they can increase the velocity to 4 – 6 m/s to remove any remaining smoke. Their conclusions for select values for ventilation to support evacuation and a suitable environment for fire extinguishing are based on tests, calculations from designers, and experience.

The interview also explained that the tunnels that allow the transport of dangerous goods are equipped with FFFS and tunnels that can include congestion. The system is deluge sector based and activated by the tunnel control central. The system has functioned well in both exercises and one actual fire incident.

Interview 2

The interviewee is an educated Fire Protection engineer with over a two-decade of working concerning tunnels and underground facilities regarding safety and emergency measures. On behalf of a fire department, as a consultant, and for tunnel authorities. During the fire department experience, the participant has experienced multiple emergencies in their tunnels, transporting 100000 vehicles per day. The majority was due to collisions but about twice a year involving fire. In all of those scenarios, the firefighting worked out quite quickly.

During his time in the industry, he has never heard of a firefighter injured during tunnel operations.

One of the scenarios involved a fire in a camper van located in tunnels equipped with FFFS that suppressed the fire until the fire department extinguished it. Afterward, that fire was inspected, and the heat release rate calculated for if the FFFS would not have been included as well as when it was included. The result showed that without suppression from the FFFS, the fire could have been around 30 MW, but with the activation of the FFFS, about 10 MW.

The interviewee thinks that modern road tunnels are well-equipped for sufficient rescue operations. He thinks that in some cases, it is even easier to deal with fire in these modern tunnels than on the surface, with chosen wind direction and velocity, a known location for water access, and sometimes even FFFS. He has, however, experience with singular tube tunnels with bi-directional traffic flow; in his opinion, they are problematic regarding safe rescue operations.

When asked about the fire departments involvement in tunnel design, the participant states that a tunnel safety specialist is included; they reach out to the governmental road tunnel specialists for experience from actual fire scenarios and give back possible new ideas. The governmental specialist includes those new solutions for safety upgrades in older tunnels. The governmental specialist has a good dialog with the fire departments regarding tunnels in their area.

When asked about pre-planned procedures in an emergency, the interviewee states that their more extensive tunnels have sophisticated control systems. When an incident occurs, the operator chooses the type of incident and the location in the tunnel, and their system will exercise everything preplanned. What he mentioned as a pre-planned example; traffic will be stopped towards the tunnels with barriers, evacuation orders will be given through speakers on the scene as well as through the vehicles radio, lightning in tunnels will brighten, ventilation set to fixed velocity, and if equipped with FFFS they are activated.

When asked for what ventilation velocity they use directly after confirmation of fire, the participant said 3 m/s if they have a possible fire alarm through as an example, heat sensing cables or removed fire extinguisher, but the operators are not able to confirm it, the air velocity is minimized and the ventilation system set to be ready for starting up to 3 m/s when and if the fire is confirmed.

For further knowledge of how the criteria for ventilation velocity is chosen, the interviewee was asked how they came to that conclusion; the interviewee said that the chosen velocity was initially from designing ventilation for controlling the back layer in tunnels with a possible 100 MW fire, in another newer tunnel they designed the ventilation for 1,5 m/s to support vehicles evacuating downstream in tunnels including congestion. After reviewing actual fire scenarios, experiencing quite bad visibility in the zone where the FFFS is activated, it was chosen to increase the velocity in the latter mentioned tunnels, even if the tunnels were congested downstream. They experience more diluted smoke, better visibility, and lower gas temperatures.

When asked if they have experienced faster fire growth due to higher velocity or if traffic downstream gets the smoke over them? They have not experienced that; they have done some testing and seen that only after 1,5 m/s is the fire getting sufficient oxygen for its free burning development; regarding the traffic downstream, he mentions that 3 m/s is just below 11 km/hr. And that they think it is not over the average speed of congested traffic.

When asked about the ventilation velocity after the fire departments arrival, the interviewee says it is the scene command to decide. They can use the radio to ask the operator to change the ventilation velocity. In his experience, they do not ask for the velocity to be changed until the fire has been extinguished, then to ventilate all remaining smoke.

They have not experienced smoke moving between portals during smoke ventilation because the ventilation in the smoke-free tube is reversed, so both tubes are ventilated in the same direction.

When asked about their FFFS system, their experience is that with this low-pressure, large droplet section-based system, the visibility is good enough to activate it early, even with traffic evacuating. Doing so fulfills the critical task of attacking the fire as early as possible. In their tunnels, personnel from the tunnel control authority in the neighborhood respond to all incidents; in case of a fire, they assist the fire department if manual control is needed for the FFFS system. The FFFS is divided into sections along their tunnels; each section is around 50 – 75 meters, depending on the distance between emergency exits.

In the case of traffic with hazardous chemicals in tunnels, there are separate pre-planned procedures; they have many similarities with procedures for fire incidents but include stopping drainage pumps. If, however, there is just a spillage on the road surface, the FFFS is not activated.

When asked about the surveillance system, the interviewer states that their camera does not have the quality to identify ADR plate numbers. However, it could be possible to see if there is an orange ADR plate on the vehicle. Their surveillance system can be streamed to the fire department command central, and they are looking into if they can be streamed to the responding firetrucks. Their surveillance systems do have automatic detection on stopped vehicles and smoke.

When asked about the water access for fire departments, the interviewee says that the maximum distance is 150 meters, commonly between 100 - 150 meters, and is located by the emergency exit and a dry pipe between tubes. The first location after the portal can be up to 200 meters between the portal and the first water access point. It is also mentioned that all emergency exit doors closest to the traffic have large windows; in their tunnels, there are sometimes four doors to pass between each tube. Each emergency exit has large markings with individual numbers to use when giving the source location to the fire department.

When asked about traffic control, the interviewee says that the same authority operates the traffic towards the tunnel and the city traffic as a whole; by closing traffic further away, they think there will be considerable congestion. They can, however, close lanes of motorways toward the tunnel portals to clear them for emergency vehicles.

When asked about cross-overs for responding vehicles, the interviewee says that the fire department never wants to move their fire trucks from the smoke-free tube into the smoke-filled tube; they use the emergency exits as access points for firefighters to move between tubes. All of the tunnels provide the possibility to move between tubes outside each portal.

When asked about other types of fire detection in their tunnels, the interviewee says that their tunnels do have thermal detecting cables installed, and in one tunnel, they have a combined alarm system. The combination alarm system is connected to multiple sensors, and with the pre-decided combination of alarms, it is marked as a fire alarm. These combinations can, for example, include one emergency exit opened and a stopped vehicle detected or an emergency exit opened and the extinguisher removed. His experience is how, ever, that it gives too many false alarms, and they are, therefore, uninstalling it. A combination of thermal detection cables, smoke detection, and surveillance cameras with detection software is used for the newer tunnels.

When asked if there are control rooms close to the portals for the fire department command to use, their experience is that the fire department uses its command vehicles and the radio to instruct the tunnel control central operators on operating tunnel equipment. However, it varies between areas.

When asked about the drainage system, the interviewee said that they are designed to handle the expected amount of hazardous liquids in the tunnels; they are designed so that 10 m3 released simultaneously disappears in 2 minutes of the road surface. In his opinion, an important safety measure is minimizing the possibility of a large pool fire scenario.

When asked about upgrades for older tunnels, the participant mentioned some difficulties regarding closing them during the upgrade, where about 100000 vehicles are passing through daily.

Interview 3

The interviewee is an educated engineer with vast experience in management for heavy infrastructure as a project manager, involved in design phases, both regarding road and rail traffic, and the latest years in tunnel safety management. There are fewer than ten incidents in their twin-tube road tunnel; one of them included a fire in a personal vehicle. None of them or their exercises have included injuries among firefighters.

According to the interviewee, there is a good dialog and collaboration between the tunnel owners and the local fire departments when pre-planned emergency plans are drawn up. The same goes for exercises, where shared experience is also at hand.

When asked about the feeling about tunnel safety measures and upgrade over the years, it is stated that there are not many possibilities regarding structural upgrades. Still, they are always looking for improvements and mainly regarding procedures, signaling, and evacuation route functions; it is also mentioned that currently, there is an upgrade going on regarding improved quality in their surveillance system.

According to the interviewee, they have 24-hour surveillance covering all the tunnels. When the operators confirm incidents, they type all information into their program, which shares the information with needed authorities; police, fire department, and hospitals. Their cameras are located in the ceiling and therefore get blocked if smoke builds up, which they are looking into, regarding the better position, at the moment. It is also mentioned that they can stream their surveillance feed to the rescue services.

When asked about their procedure during incidents, it is stated that their standard procedure is to close both tubes during incidents, therefore getting the tube not involved free of traffic and ready to be used for responding units. To shorten the response time, an adjacent traffic lane toward one of the portals is closed so the fire department can drive shorter distances against regular traffic and flow towards the portal. To support the safety of traffics and the fire department, there is a unique traffic light that the operator activates to ensure the fire truck driver that the next lane is free of traffic. When arriving at the portal, the fire department is directed to the smoke-free tube. All dialog is via radio, but as an additive, they illuminate the emergency access closest to the source.

According to the interviewee, a further emergency procedure is to ventilate with the traffic flow, most often 3 – 4 m/s but turned down if requested by the fire department or if one tube is used for both traffic directions due to maintenance in the other. This is something that is being evaluated regarding the risk of turbulence and mixing smoke gasses instead of more laminar flow. When asked about the ventilation setting in the smoke-free tube when the fire is confirmed, it is mentioned that the ventilation is usually not changed until the fire department asks for it. When asked about ventilation strategies in case of toxic or flammable gas leakages, the interviewee mentioned that their jet fans are not rated for flammable gases. Therefore they use the push method while ventilating gasses out.

When asked how the procedure is regarding emergency calls from the tunnels. The participant mentioned that if they are made by the emergency phones in the tunnel, the tunnel control center receives the call; however, if it is made by cell phone to the countries emergency number, the emergency center will contact the tunnel control center immediately. According to the participant, it is doubtful that the operatives at the tunnel control centers are unaware of the incident. Their surveillance system has software that detects abnormalities in the tunnel traffic. If something is detected, it is prompted on the screen at the tunnel control central, and the operative is alarmed.

The software used for tunnel control central operators allows the operator to, when an emergency occurs, choose the type of incident and is then guided by a pre-programmed checklist; the system then surveils that everything is done correctly. Their system can also read ADR labels and identify their numbers; when a fire occurs, they have a list of ADR vehicles possibly close to the scene. The interviewee, however, mentions that this program is not without faults.

The participant states that their emergency exits are located throughout the tunnels, with around 86 meters between them; there is access to water for the fire department at each location. Between each tunnel is an escape tunnel with overpressure to minimize the possibility of smoke getting in.

When asked about other types of detection than surveillance cameras, the participant states that they have other types of fire detectors; what type of fire detection is not mentioned; these detectors alarm the fire department directly, but most often, the tunnel control center can confirm if it is a false alarm before they have left the fire station.

When asked about other equipment in their tunnels, the interviewee stated that their tunnels are not equipped with FFFS, they do have the equipment to support the fire departments communication system, and there are electrical sockets for electrical equipment. However, these sockets are not used, whereas the fire departments use their own electrical generators.

Interview 4

The interviewee is educated in civil engineering, with nearly two decades of experience, including project management during tunnel construction, maintaining management for tunnels, regarding tunnel fire protection, and organizing emergency response exercises with the fire departments and latest years working as a safety manager for multiple tunnels over 500 meters long and many of them twin-tube tunnels.

When asked about incidents, the interviewee states that many collisions and fires have occurred. It has been a while since the latest severe fire incident occurred, but the latest fire-related incidents have been more minor and extinguished without significant consequences. These incidents are related to smaller vehicles and heavy goods vehicles.

When asked about his feeling regarding how safe their tunnels are, then referring to the twin-tube tunnels, the participant states that he feels they are safe and that the equipment being used is suitable.

Concerning exercises, the interviewee stated that there are smaller exercises every year for each type of tunnel and extended exercises every other year. It is mentioned that it can be difficult for the fire departments to be available where they are under some pressure of exercising all kinds of other scenarios not tunnel related. However, they have one tunnel dedicated to training, which is included in their firefighting education, allowing them to run approximately 30 to 45 firefighters through exercises with realistic environments every year.

Regarding the path that emergency calls take, the interview states that their emergency phones in the tunnel are directly connected to their tunnel control central, which alarms the needed authorities, including hospitals. If an individual calls the national emergency center, their operators alarm the tunnel control center.

When asked about pre-planned emergency plans, it is stated that these plans are designed in collaboration with the fire department. During incidents, after the needed authorities have been notified, the operatives at the tunnel control central close the tunnels and start analyzing the scene. All gathered information is passed, by radio, to responding units. Valuable information is mentioned where; what is happening, how many vehicles are stuck in the tunnel, and how the evacuation functions. These plans do not involve any traffic control further away from the portals other than closing towards the portals.

The ventilation is stated to always be in the direction of the traffic flow; after confirmation of fire, the ventilation is set to 1 to 3,5 m/s. Their ventilation can get that flow even with natural wind working against it. It is also mentioned that the smoke-free tube ventilation is reversed to ventilate in the same direction as the tube under fire; by doing so, they do not get smoke moving between portals.

When asked about pre-planned procedures in case of chemical leakages, the interviewer mentioned using ventilation to ventilate the toxins and then relay them to the fire department for further instructions. The interviewee also mentioned that they have not much experience with such incidents.

Their tunnels are equipped with surveillance cameras and, in some cases, infrared cameras, and their feed is run through automatic incident detection software. As well as stream the surveillance feed to the emergency operations center and responding units if they are equipped and known to receive it. It is also mentioned that one of the features in automatic incident detection is the detection of smoke; that feature has been giving a lot of false alarms due to large vehicles blocking its sight.

When asked about other detection equipment like thermal measuring cables, the interviewee mentioned that they are not experienced or commonly used.

Regarding water access for the fire departments, the interviewee said they were located every 250 meters, for twin-tube tunnels built last 20 years, along with the emergency exits.

It is stated by the interviewee that in their twin-tube tunnels longer than 1500 meters, there is an availability to drive response vehicles between tubes as the European regulations require. Their tunnels are also equipped with control panels for the fire department to adjust some settings regarding ventilation and broadcast announcements to users. The interviewee mentioned that the incident commanders are not adjusting themselves and have many other tasks to focus on. Therefore, they communicate to the tunnel control central to adjust settings.

In his experience, the fire department is not delayed by congested tunnels, referring to the fact that most often they are arriving from separate directions, allowing at least one of them to drive with the traffic flow and where usually there are at least two lanes, the traffic can move aside.

Interview 5

The interviewee is an educated Fire Protection Engineer with nearly three decades of experience in firefighting and incident management on all levels. Then involved in tunnel projects, tunnel safety, and forming tunnel emergency response tactics.

The interviewee has experienced being in command of a couple of incidents in road tunnels but thinks that their design is on the right path regarding firefighters safety and supporting their efficiency. However, feeling that the alertness regarding the issue is slightly lowering. He does not know firefighters getting injured during tunnel incidents.

According to the interviewee, their twin-tube tunnels are designed so that the firefighters can get their vehicle close to the incident source by the use of the smoke-free tube, have water access by the emergency exits, pump the pressurized water from the firetruck between tubes by a dry pipe; BA-teams can then move between tubes through the emergency exits and connect their hose on the other side and start their approach. Their standard is 150 meters between emergency exits, providing not too long an approach distance and a reasonably good environment in high-risk situations. When asked about the availability to access water in more detail, the interviewee mentioned that hydrants are located at each emergency exit and have a dry pipe between tubes. The dry pipes are colored red, and the hydrants are colored blue to prevent faulty connections.

When asked about collaboration between the fire department, owners, and designers during tunnel design, the interviewee says that there is a tendency to try to cut costs in safety measures, where they can be costly. But they do, however, listen to the reasoning of the fire departments. For example, about a decade ago, new tunnels were to be constructed with the idea that firefighters would have a 500 – 1000 meters path to move in a smoke-filled environment to extinguish a fire and search and rescue for trapped evacuees. After hearing how BA operations are proceeded and the availability of time for each BA-team, the designers realized it was not functioning.

When an emergency call is made directly to the emergency center, their procedure is to alarm needed authorities and the tunnel control central. If the call is made by one of the tunnel emergency phones, it goes directly to the tunnel control central, and their operatives will alarm needed authorities.

When asked about their tactics when a fire has been confirmed in tunnels, the interviewee said they usually dispatch three firefighting units and two incident commanders toward the scene. The first firefighting unit arriving is asked to get as close to the fire source upstream by using the smoke-free tube and to start extinguishing procedures. The second firefighting unit arriving is asked to get close to the fire source downstream by using the smoke-free tube and start search and rescue for evacuees in trouble. The third firefighting unit is asked to halt at the portal and use it where needed. The incident commanders choose their suitable command posts at the portals. The interviewee also mentioned their principle to use smoke-free tubes when approaching the source and never to drive their vehicles in the tube under fire. The standard procedure for ventilation is when there is a confirmed fire. Before the fire departments arrival, the ventilation is set to fire mode; the velocity is slowed to increase laminated flow and prevent backlayering around the fire to support evacuation. The velocity used in fire mode is around 3 m/s. After the fire departments arrive, they decide what setting should be used for the ventilation and the activation of sprinklers. If they are not confident that the evacuation process has finished or do not have control over the fire, the ventilation velocity is never asked to be increased; the reason given is increased heat release with higher velocity. It is also mentioned that the ventilation is often not adjusted after the fire departments arrive. When asked about experiencing smoke moving between portals, the interviewee recalled one incident where much black smoke poured from the tube under fire and turned inwards to the unaffected tube. Regarding countermeasures for this scenario, the interviewee was not sure but thought that some of the jet fans in the unaffected tube are being reversed; however, he mentioned that the whole system is not reversed where it is much mass in the moving air and can be challenging to reverse the whole length of the tube.

When asked about exercises, the interviewee said they are not frequent enough; extended exercises every other year are located in one of their tunnels with cold smoke. Involving the tunnel administration, police, ambulance services, and one shift from two to four stations, resulting in too long intervals to give all firefighters experience. Regarding what information the interviewee thinks it is of the essence for responding units, the location of the fire source, which tube should be used for a safe approach, and where each unit should head is the first thing mentioned, secondly that there is an excellent dialog to the tunnel control central regarding what road closing booms need to be opened for responding units arriving. Their dialog is stated to usually be by cell phone or radio to their dispatch center. When asked about the possibility of the fire department adjusting the setting on the scene regarding tunnel equipment, it is stated that it is practically possible to override the systems manually. If they are to be adjusted, the incident commander contacts their dispatch center, which forwards his request to the tunnel control center. When asked if they have special equipment for tunnel emergencies, the interviewee said they do not. When they are involved in new tunnel projects, they claim that they will not be able to have any special equipment for tunnel firefighting in the future. And that the structure design will need to be adapted to their possibilities. They aim to use the same equipment as when fighting residential fires, previously water mixed with foam (CAFS) but with it being restricted today, it is more and more mainly water.

According to the interviewee, there have been some tests regarding longer travel distances in train tunnels. To send the first BA-team as a recon team, they approach the fire source only with a light rope, with integrated LED lights, and maybe a fire extinguisher. By doing so, they can travel much faster and gather information on the fire source and the scene to allow scene command to get a better image for further decisions.

When asked if they have experienced spalling from tunnel structures and how their reactions would be in such a scenario during fires in a tunnel, the interviewee states that they documented spalling during tests and exercises and that these scenarios are able. In his opinion, they should not be in the tunnels if it comes to that. Regarding hazardous chemicals and procedures, the interviewee mentioned they would have a similar approach in case of a fire and the same ventilation strategy.

When asked what information is available for the responding units, the interviewee stated that their vehicles have .pdf files in their vehicle computers with all layouts and information about their tunnels; these documents are available at their stations.

Regarding other installations, the interviewee mentioned that communications in their road tunnels are functioning, as their tunnels are equipped with signal-strengthening technic where it is needed. When asked about the information regarding what emergency exit they should use as an access point, the interviewee mentioned that all emergency exits are numbered, and the number closest to the source is passed to the responding units. However, it is also mentioned that giving clear and accurate information to responding units regarding which tube is safe to enter is vital.

The interviewee mentioned tests on mobile jet blowers as an alternative to ventilation in tunnels; in his experience, they are great for increasing ventilation velocity, but they take time to deploy and form much noise., the interviewee mentioned again that it is better to support the efficiency of fire departments that these technical aids are integrated into the structure from the beginning.

When asked about the possibilities of detecting evacuees in a smoke-filled environment, the interviewee mentioned emergency exit door detection as one of them—and added that it is essential that the tunnel control center operatives are well-trained and that they can do much work during emergencies.

Regarding traffic control outside tunnels and the possibilities for responding vehicles to approach. The interviewee mentioned that in most cases, there are two lanes toward the portals allowing responding vehicles to bypass the stopped traffic; close to the portals, there is a possibility to move between portals if needed to use the unaffected tube. He mentioned that during some incidents and due to poor communications with the tunnel control central, they had to wait after them to open the barriers. The interviewee agreed when asked if traffic congestion could delay their arrival time—then mentioned that when a fire occurs in tunnels, it is a standard routine to close both tubes for them to be evacuated, which will build up congestion outside the tunnels affects their arrival time. The interviewee did not think that traffic downstream of the fire source is having trouble evacuating with their vehicles due to heavy traffic and that it could affect the whole traffic system if there were some traffic control modifications far away from the tunnel when incidents occur.

The interviewee has not experienced the function of FFFS in their tunnels in real cases but has seen tests that show good results and function. At the end of the interview, it is mentioned that fire incidents in tunnels are unlikely, but when they occur, they tend to be problematic and involve high risks.

Interview 6

The interviewee is an educated Mechanical Engineer with nearly three decades of experience in air fleet maintenance and has been working in the firefighting field for the last decade. Last years as an incident commander.

In their area, there are three singular tube tunnels with bi-directional traffic. In his time, there have been a couple of accidents, but none, including fires.

When the interviewee is asked about his feeling regarding design measurements supporting firefighting safety and efficiency, it is mentioned that when their older tunnels are compared to the newly updated ones, it is like day and night. And that the updated ones are very good.

When working on pre-planned procedures, there is a dialog to strengthen their collaboration with tunnel management, but today, they have limited collaboration.

When asked about exercises, the interviewee said they exercise once every year, with every other year being an extended version and lighter exercises between; when done in tunnels generally used for traffic, they use cold smoke as well as having access to special exercise tunnels every year where they can use actual fire for a realistic environment.

When asked if they have any special equipment for tunnel emergencies, the interviewee mentioned an ATV, tanker with water and foam cannon; these vehicles are also used for other cases if needed.

When asked what procedures they have for spalling in a tunnel environment, the interviewee said they are always alert about the risk of spalling or equipment falling and its relation to high heat release from the fire; if it would be a high density of smoke, they would carefully move forward.

When asked about their involvement in new tunnel structures, the interviewee said they are involved later, in the final stage, where there is a dialog regarding what equipment should be installed in the tunnels and their settings. It is, however, their wish to be more involved from the beginning.

Their tunnels have different coverage of surveillance systems; one newly updated tunnel has 100% coverage, the others with only portal surveillance, and one of that surveillance is in the middle section. When asked about the difference in emergency operations, the interviewee mentioned that when the tunnel control center has full coverage, they can provide vital information regarding the scene and think it is crucial for operational decisions. In the tunnels with less surveillance coverage, the only way to know if there are people inside the tunnels is by indication of extinguisher removal or a phone call made from one of the emergency phones located in the tunnels.

When asked about water access, the interviewee mentioned that they have to bring all water with them to the tunnels. It is also mentioned that the procedure is to close the tunnels with blinking lights and booms at the portals. Their surveillance system is connected to software to identify abnormalities in the tunnels. When an incident occurs in the tunnels with full surveillance coverage, the operators try to identify if there are any vehicles marked with ADR labels; if so, they can call the transport company and ask for what type of dangerous goods the vehicle is carrying.

All information regarding the tunnels and their equipment is available in the fire trucks, there are technical rooms located outside the portals, but they tend to use their vehicles and radio communication to the tunnel control central; however, the communication to the tunnel control central is lost, they can use those rooms to adjust setting for the ventilation.

Interview 7

The interviewee is about three decates of experience recarding technical installations and safety equipment installation in tunnels. First as an contractor and later as an consultant for the countries road administration and along with consulting, lead a working group regarding tunnels safety for a decate.

When asked about previous incidents, the interviewee recalled couple of personal vehicles burning, but nothing that was difficult to extinguish. Mentioning that due to the reason that most of their tunnels are two tube tunnels with the traffic flow seperated, the accident frequency is lower and working environment for the fire department way better. Stating that the most important safety measure in tunnels is to have them two-tube.

Regarding how to support firefighters safety and efficiency the interviewee mentioned that there is a constant dialog about; the distance between emergency exits/access, distance and location of water access points and how much waterflow should be availible at each water access point. The interviewee said that there seems to be the tendency to constantly add new safety measures, but other previously added safety measures technology are not removed, even though the newer safety measure covers the function of the previous one.

Most of the incident detections are by the automatic detections system, intergrated in the vide surveilance system. However when there is a traffic congestions multible times per day, the system can miss detection and the alarm arrives by phone from tunnel users before the system detects.

Their tunnels are also equipped with fiber optic cable for thermal detection, alarming the tunnel control central if there is a fast temperature increase or if the temperature rises above 50°C.

When asked about collaboration with the fire department during design of new tunnels, the interviewee mentioned that they are not involved in the early phase but a bit later on. They have however regulations to fulfill, that involve the fire departments safety and efficiency.

Regarding the procedures that take place in emergency, the interviewee stated that the tunnel control central operator only has to press one button and choose location inside the tunnels. After that the computer system initates the emergency procedure by, increasing the lightning, start ventilation, closing the portal barriers and starting evacuation. After that the operator tries to signal stuck tunnels users to leave their vehicles and evacuate, according to the interviewee, the problem is to get people to leave their vehicles.

According to the interviewee there has been tryouts to text different ways to identify the ADR plates on vehicles entering their tunnels, it has however not been as efficient as they want. In case of emergency their operators try to identify the vehicles around the fire to bring up information to the responding units.

When the interviewee is asked about his feeling regarding equipment installations in newer tunnels, if they are sufficient or if there is a need to improve the used equippment or technilogy. The interviewee stated that in his opinion the equipment is sufficient and most often working as it should, however the connection between technical parts or equippment and the organizations needs to be improved. To minimize the differenc in function and equippment controling between different tunnels, to refer to simular settings in all tunnels to increase the efficiency of the fire department. As an example the interviewee mentioned the diffirence in definition of the preferred ventilation output, in some cases the output is chosen by preprogrammed steps, f.ex. 1 to 5 and another tunnel the ventilation output is defined by percentage output of the jetfans.

When asked about the preferred value for the ventilation velocity during emergency, the interviewee mentioned that the prefer 1,5 m/s in the traffic flow direction in the first phase. After the fire departments arrival they can increase it up to 3 m/s in the request. When asked about if the ventilation is always in the traffic flow direction, the interviewee mentioned that in one of their tunnel the procedure is to turn the ventilation direction towards the closest portal the fire is in the first 20-25 meters from the portal. If the fire is however 50 meters inside the tunnel the ventilation direction is always along the traffic flow.

According to the interviewee they are able to control the ventilation direction even if there are strong natural winds against the portal and mentioning that the problem for the ventilation can be when fighting hight temperatures and they updrift in the smoke. Their ventilation is commonly designed in relation to 100 MW fires. When asked if they have experienced smoke moving between portals, the interviewee stated they always turn the ventilation direction in the smoke free tube to ventilate in the same direction as is done in the tube undier fire. All of their tunnels are equipped with longtitudional ventilation. When asked for procedure in case of chemical leakages, it is mentioned that they try to push gasses out where the fans are note ATEX approved, to decrease risk og ignition.

Regarding if the on scene commander can change the settings of the ventilation on site, the interviewee mentioned that they had such possibility 10 years ago, but because it was seldom used and thought to be easier to ask the tunnel traffic control to change those settings they have not included such settup in newer tunnels.

When asked about the distance between the emergency exits and if there is a water access in their tunnels the interviewee stated that there is about 100 m between all emergency exits and that there is a water access point at each emergency exit.

Regarding traffic congestions in their tunnels and the possibilities to approach the tunnels in heavy traffic the interviewee mentioned that in all of their tunnels the fire department is able to approach from both portal ends and therefore one is most commonly not involved in heavy traffic. Giving them the oportunity to arrive within 10 minutes. They are constantly looking into possibilities to assist possible evacuation in congested tunnels, both by how the layout of the tunnel is set up and by the traffic network arount the tunnels.

When asked about safety upgrades over the years, the interviewee stated that there is always some work going on to find better solutions for increasing safety.

Interview 8

The interviewee is an educated engineer with about a decated of experience working for the fire department, first as an fire inspector and now as an incident commander and underground facilities specialist regarding safety and emergency measures.

The interviewee mentioned that luckily they have not experienced severe fire or chemical incidents in their road traffic tunnels. The incidents that have occurred are mainly due to traffic accidents.

In the interviewees location there is a multiple underground facilities, as for this interview the focus is set on a two-tube road traffic tunnels. One of the tunnel in the interviewees area is close to 2 km in length, connecting their harbour area to the city. Therefore with high frequency of heavy goods transport vehicles and transport of dangerous goods.

The interviewees opinion is that the design on their modern road traffic tunnels is on a good path regarding safety and efficiency for their firefighters. Then mentioned that more exercises is needed for all of those involved. The interviewee mentioned that their involvement in new tunnel projects is from the early beginning, working together with the city planners and designers to find appropriated solutions that all parties agree upon. When asked about how often they exercise regarding each tunnel setup, the interviewee mentioned that they have one scheduled training each year, only able to give one shift experience each time. When doing such exercises, most commonly only cold smoke is generated with smoke grenades to simmulate the scenario.

As for equipment their fire department has, aimed at tunnel emergencies. It is mentioned that their fire trucks are intergrated with large smoke ventilators, however there is seldom need for that in road traffic tunnels where the tunnels most commonly have their own ventilation system. Another mentioned tunnel tactic and equipment is that all of their BA-teams have the knowledge and equipment to doubble up their air capacity for longer periods of work in contaminated air.

It is mentioned that their lighter trucks is equipped with CAFS foam system, but their most commonly used method and their aim is to use water. They have not experienced the need for other extinguishing materials in underground fires.

When asked about their tachtics in case of spalling or equipmment falling in front of BA-teams, the interviewee mentioned their tachtics depend on the situation. Is there are evacuees in distress and the type or size of spalling or equipment falling. They do risk assessment to take decisions for choosing further tachtics.

For when there is a potential chemical leakage in their tunnels the interviewee mentrioned that the main difference in they tachtics lies within the tunnel control center operations, where they follow different manuals for controling intergrated equippment.

Regarding what information the incident commander preferes to get for when answering an emergency in tunnels, the interviewee mentioned that in the first phase, the location of incident, type if scenario, direction of smoke ventilation and if there are evacuees in distress is a valuable information.

When asked about pre-planned emergency procedures, the interviewee states that they have maps for all of their tunnels, showing vital information regarding emergency response and availible equipment. These documents are made by the fire department and sometimes in cooperation with the tunnel owner. When incident commanders arrive at scene there are red boxes with maps of the tunnel availible at the tunnel portal. However their commanders are not able to see the video feed from the tunnel surveilance cameras which is a problem according to the interviewee.

Their TETRA radio signal is boosted in the tunnels if needed with so called leaking cables, the interviewee mentioned that in the next years they will be taking up communications in 5G and that such technology would increase the radio coverage.

The interviewee mentioned that the use of thermal camera is vital in locating the fire source in tunnels and that it on of the most cruisial equipment in taking decisions where to fill up their water hoses. Mentioning that if they are filled up to early there can be a time delay for if they need to be emptied and refilled again.

For locating right emergency access point for when travelling through the smoke free tube towards the incident source, the interviewee mentioned that the cooperation with the tunnel control central is vital. They will then guide the fire department to the right portal and depth. The distance between emergency exits and water access points is mentioned to be 100 meters, and that it supports the evacuation and the fire departments operations to have such short distance between exits/access points.

When asked about the what equipment the inteviewee thinks that is more importand than other regarding firefighters safety and efficiency, the interviewee mentioned the smoke ventilation to be the main design measure and that it is vital that it is functioning as it is designed. As an second thing, the water access for the firefighter is mentioned to be of a importance.

For the preferred value of ventilation during emergencies, the interviewee mentioned that after confirmation of the emergency and before the arrival of the fire department the preferred ventilation velocity is 2 m/s in the traffic flow direction, if the tunnel control central sees through the surveilance video feed that 2 m/s is not holding back the backlayering, they can increase the ventilation up to 3 m/s. After the evacuation has finished and the fire department has arrived the ventilation is preferred to be set to 3 m/s. These velocity values are chosen from regulations and recommendations from other Nordic countries. The interviewee mentioned however that each scenario is different and chosen velocity is dependand on the scenario. To prevent that smoke moves into the smoke free tube thought the portals, the ventilation in the smoke free tube is reversed and ventilated in the same direction as the tube under fire. Their incident commanders have the oportunity to control the ventilation on site, but most commonly they prefer to do ventilation changes through the radio to the tunnel control central.

When asked about what tachtics they aim to use, the interviewee mentioned that is depends on the resources availible as well as the type of scenario. Most commonly the first team arriving starts to approach the fire for extinguishment, while the second arriving team assissts the evacuation if needed. If however people are seen to be in distress in the smoke, search and rescue becomes the main goal.

The interviewee mentioned that during tunnel closure in rush hours, long traffic lanes are quick to form and can delay the fire departments arrival time by couple of minutes. The cooperation between tunnel control central, the police, the ambulance service and the fire department is thought to be working well in most cases. The tunnel control central is mentioned to try to guide the traffic to other roads, using radio anoncements, social media and traffic lights. Usually the police is however needed for the task as well. The tunnel control central is also mentioned to try to open up traffic flow out of the tube under fire, by switching traffic lights for the evacuationg traffic to green.

Their tunnels are equipped with automatic incident detection system, intergrated in their surveilance system, proviting quick detection in case of abnormalities in the traffic flow.

In one of their tunnels there is the availibility to drive emergency vehicles between tubes inside the tunnels, but due to maintanance difficulties and no usages they option has been disabled. The interviewee mentioned that they do not prefer to move the fire trucks between tubes, but use the emergency exits/access to move the BA-teams between tubes. Therefore keeping the truck and other personel in smoke free environment.

Most commonly their tunnels are equipped with longtitudional ventilation, one of their tunnels is however equipped with transversal ventilation. According to the interviewee the transversal ventilation they have there is not functioning as well as they would like.

The interviewee mentioned that in the tunnel that has the hight frequent transport of dangerous chemicals, each tube dranages system is served by 180 m^3 tank for dangerous liquid leakage and used firewater. Allowing the drainage system pumps to be shut off while the fire department operates.

Interview 9

The interviewee is an experienced firefighter and a special unit leader focusing on intensive operations where long durations of BA operations are required. According to the interviewee, they only use OBA equipment during their operations, allowing up to four hours of BA operations. The interviewee says he have not been involved in many twin-tube road tunnel operations, but he has more experience regarding train tunnels and other underground facilities. He also mentioned that in tunnel operation, his unit is an additive to regular firefighting units.

When asked about his feeling regarding exercise intervals and the availability to exercise in the actual tunnel environment, the interviewee states that it is essential to have access to exercise in the same environment as it could be under fire. He also mentions the importance of every firefighter being familiar with the procedures and that one operation management failure can lead to horrific scenarios.

Regarding equipment in twin-tube road tunnels in their area and his feeling about providing a safer environment for firefighters and supporting their safety, the interviewee thinks they are generally sufficient. However, they mentioned that in their train tunnels, there are some difficulties regarding ventilation and water access points. One of the most problematic regarding those train tunnel scenarios is knowing when to fill up their water hose system, where it can develop a long delay to fill the system too early and not be able to reach the source of the fire.

When extinguishing tunnel fires, they aim to use only water; each BA-team is equipped with an infrared camera.

When asked about traffic control toward their road tunnels and their possibilities to get through the traffic, the interviewee mentioned that the tunnel control center has excellent availability and instructions for them to bypass congested traffic. Opening and closing routes for them to use, mentioning that in one section, the tunnel control central can clean out traffic lanes to allow responding units to drive against normal traffic flow for a shorter distance towards the tunnels.

The interviewee also mentioned the high-stress level and draining for firefighters when working in a smoke-filled environment, not mentioning if there are possible casualties involved. It may be easy to do theoretically or on an open road but more difficult in an actual tunnel scenario.