Fire incidents during construction work of tunnels - evacuation aspects

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Abstract

The report focuses on evacuation aspects at tunnel construction sites. An introduction provides a framework on what determines the outcome of an evacuation, i.e. the physical environment and management aspects. Analyses of the evacuation conditions for several fire scenarios are performed using a combined smoke spread and evacuation model developed as a part of the project. Finally, general recommendations on how to analyse the evacuation safety in a specific tunnel is provided.

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Preface

The report is a part of the results from a research project aiming at investigating fire safety issues related to tunnels being constructed. The project has covered aspects as fire development, occupant safety and evacuation aspects and finally aspects related to the intervention by the rescue services. The project has been financed by MSB – Swedish Civil Contingencies Agency and has been running between 2008 and 2010. The project has been led by Professor Haukur Ingason at SP Technical Research Institute of Sweden and been involving researchers at also Mälardalens högskola.

This report dealing with evacuation safety is one of several publications in the project. An overview of the complete research project can be found in the main report, Ingason, Lönnermark, Frantzich & Kumm (2010).

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Summary

A tunnel construction site may be seen as an example of a complex environment. It can therefore be assumed that in the case of a fire the evacuation from the different locations within the construction site is more difficult than if the tunnel construction is finished. Most attention regarding fire evacuation research has been on public buildings and in the case for tunnels, on tunnels in operation. It is, therefore, needed to perform evacuation research in this more complex environment.

Due to the complex nature of a construction site, evacuation conditions for people working at construction sites are more complicated than can be expected in public buildings or tunnels in operation. The complexity at a tunnel construction site makes evacuation more difficult due to both cognitive and physical obstacles. For example, a construction site is constantly changing, which means that the evacuation routes can be modified from one day to another and may not always be clearly marked. This type of constant modification can make way-finding problematic. This site-specific conditions have to be considered when designing a management strategy for handling the safety in the case of a fire for the workers at the tunnel construction site.

The evacuation situation for workers at a tunnel construction site is analysed by a theoretical approach, by physical experiments and by modelling the situation. It is determined that the evacuation depends on both the physical conditions and by aspects originating from a management perspective. Parameters affecting the ability to evacuate can depend on the physical movement conditions, visibility in the tunnel both with and without smoke, the noise level and communication installations.

Aspects related to management issues are for example training and performance of evacuation exercises. Also the use of a systematic management approach on how to handle fire related questions are vital in order to provide for a safe working environment.

To analyse the evacuation situation in the case a fire occurs two modelling approaches have been used. A comprehensive model was developed to combine a smoke spread model and an evacuation model. The model assumes that smoke is transported from the location of fire by the artificial draught created by the fresh air ventilation system in the tunnel. The fresh air system is used to create a good environment for the persons working in the tunnel during the normal conditions. The evacuation is assumed to start after a determined pre-movement time and continues as long as the accumulation of toxic products has not reached hazardous levels. Account is taken to how low visibility affects the movement velocity.

The fire safety model was used to determine the possibility to evacuate from the location of work to a safe location. Mostly the fire was located in the vicinity of the work place in the most remote part of the tunnel. Four fire scenarios was part of the analysis; fire in a drilling rig, fire in two passenger cars, fire in an articulated hauler and a fire in a passenger bus. The developed model was then used to perform a sensitivity analysis changing both factors related to the fires and factors related to evacuation capability. In most cases where the evacuation had to be performed in the smoke zone the situation for evacuation were difficult. In cases where a fast response by the workers could be anticipated, they could escape ahead of the smoke zone providing a better chance of arriving to a safe location.

In order to determine the conditions for the case where the fire, located away from the place of work, affected the persons in the tunnel in the situation when the fire destroys the fresh air tube beneath the tunnel ceiling an additional set of calculations were performed. The purpose was mainly to determine if smoke continue to move further into the tunnel when the air movement changes due to the destroyed air tube. The calculations showed that the smoke spread situation changes dramatically when this situation occurs. A rapid change of the smoke movement situation can have a serious affect on the ability to evacuate the tunnel.

The results from the analysis is that there is a clear need for a fire warning system at tunnel construction sites. If an evacuation can start early in the fire development process there are good chances that the persons can evacuate safely. The persons can either move to a safe escape route or to a refuge chamber. Sample calculations provide information on how to locate those safe locations.

Sammanfattning

En tunnelarbetsplats kan anses vara ett exempel på en komplicerad miljö sett ur ett utrymningsperspektiv. Det kan därför antas att utrymning från en sådan plats kan se annorlunda ut jämfört med utrymning från publika byggnader eller tunnlar som tagits i drift. Den mesta forskningen som genomförts ur ett utrymningsperspektiv har dock fokuserat på förhållanden som varit under normal drift. Därför finns det anledning att vidga perspektivet och förbättra kunskapsläget för mer komplicerade miljöer.

På grund av den komplicerade miljön kan det antas att utrymningen från en tunnelarbetsplats är förenad med större svårigheter jämfört med t ex en publik byggnad. Det som gör utrymningen mer komplicerad kan bero på antingen fysiska eller kognitiva hinder. Exempel på svårigheter kan vara att en byggarbetsplats ständigt förändras vilket innebär att vägledning av utrymningsvägar kan bli felaktiga. För att utrymningen ändå ska kunna ske på ett tillfredsställande sätt måste dessa problem beaktas i samband med arbetsmiljöarbetet.

Möjligheten att utrymma från en tunnelarbetsplats har studerats såväl teoretiskt som med hjälp av experiment och beräkningsmodeller. Ur ett teoretiskt perspektiv kan det konstateras att de problem som finns med utrymningssituationen kan delas upp i fysiska orsaker och ledningsrelaterade orsaker. Exempel på sådana fysiska orsaker är faktorer som beror på svårigheter att förflytta sig, hög ljudnivå, dålig sikt och svårigheter med kommunikation. Bland de ledningsrelaterade orsakerna finns svårigheter att nå ut med utbildningsinsatser, genomförande av utrymningsövningar samt svårigheter i samband med ett systematiskt arbetsmiljöarbete.

För att analysera säkerheten för utrymmande personer har i princip två olika modelleringstekniker använts. En förenklad utrymningsmodell utvecklades vilken beaktar såväl brandgasspridning i tunneln och utrymningen som förväntas ske. Modellen hanterar därför dessa båda aspekter samtidigt. Modellen antar att brandgaserna transporteras med det luftdrag som skapas av den mekaniska ventilationen på arbetsplatsen. Mekanisk ventilation finns som förser alla arbetsplatser med frisk luft via ett rörsystem under taket i tunneln. Ventilationen används för att skapa en bra arbetsmiljö vid normal aktivitet i tunneln. Modellen antar att utrymningen inleds efter en förutbestämd fördröjningstid som ska beakta personernas varseblivning och förberedelser inför utrymningen. Utrymning kan ske så länge inte kritiska nivåer för utrymningen uppnåtts. Modellen tar hänsyn till att gånghastigheten i den rökfyllda miljön påverkas av dålig sikt.

Den förenklade utrymningsmodellen användes för att bedöma möjligheterna att utrymma från olika platser i tunneln. I de flesta fall var den antagna branden placerad i anslutning till den aktuella arbetsplatsen längst inne i tunneln. Fyra brandscenarier undersöktes; brand i borrigg, brand i två personbilar, brand i en dumper och brand i en buss. Analysen genomfördes som en känslighetsanalys för att undersöka effekten av olika förhållanden. Såväl brandrelaterade som utrymningsrelaterade variabler ändrades under analysens gång. Det kan konstateras att om utrymning sker genom brandgaser så är det under mycket svåra förhållanden. Om det kan förväntas att utrymningen inleds snabbt kan personerna utrymma framför området med brandgaser och då hinna sätta sig i säkerhet.

För att undersöka fallet då branden uppstår på en plats mellan tunnelmynningen och arbetsplatsen längst inne i tunneln har några enklare CFD-beräkningar genomförts. Avsikten med dessa var att undersöka vad som händer med brandgasspridningen om röret som förser arbetsplatsen med frisk luft brinner av ovanför branden. Frågeställningen som undersöktes var om brandgaserna vänder vid brandplatsen och följer med luftströmmen ut eller om rörelsemängden i luften som strömmar ut från det trasiga röret skickar brandgaserna in i tunneln mot arbetsplatsen. Beräkningarna visade att det finns en klar möjlighet att brandgaserna fortsätter in i tunneln och riskerar därför att utsätta personer som utrymmer för en snabbt försämrad situation om de möter den snabbt annalkande luftströmmen med brandgaser.

Resultatet av utrymningsanalyserna visar på ett tydligt behov av en snabb alarmering av personerna i tunneln. Om dessa kan inleda sin utrymning tidigt finns det goda chanser att de kan ta sig till en säker plats. Denna kan utgöras av exempelvis en utrymningsväg till ett parallellt tunnelrör eller en räddningskammare. Beräkningar visar på hur långt avståndet bör vara mellan dessa säkra platser.

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1 Introduction

1.1 Background

A tunnel construction site may be seen as an example of a complex environment. It can therefore be assumed that in the case of a fire the evacuation from the different locations within the construction site can be more difficult than if the tunnel construction is finished.

By tradition most evacuation analyses have focused on the problems associated with evacuation of large populations in public environments. This is partly due to the need for building codes to rationally regulate evacuation capacity of doorways, corridors and stairways etc. Another reason for investigating the evacuation capacity for large populations is the need to find input data for egress modelling for large crowds. This has also lead to the development of several egress models, which are suited for handling large populations. The typical premises for these models are public buildings, e.g., sports arenas, mass transit systems and high rise buildings. Much attention has also been focused on places where people may not be able to evacuate by themselves, e.g., total institutions (Moss Haber, 1980), or buildings where people may not be familiar with the layout and evacuation routes, e.g., retail stores (Shields & Boyce, 2000 and Frantzich, 2001). Evacuation in these types of environments is therefore rather well-documented. However, knowledge about evacuation in industrial premises and at construction sites is relatively limited.

Evacuation conditions for people working at construction sites are very different from the conditions that can be expected in public buildings. Most importantly, the environments are sometimes very complex, i.e., difficult to evacuate due to both cognitive and physical obstacles. For example, a construction site is constantly changing, which means that the evacuation routes can be modified from one day to another and may not always be clearly marked. This type of constant modification can make way-finding problematic.

The environmental conditions may also impose other difficulties such as problems hearing an evacuation alarm because of background noise and problem moving to a place of safety due to narrow passages and obstacles in the path of travel. These types of factors make the environment complex with regards to fire evacuation, which can form extra hazards that have to be dealt with during operation in the complex space.

Much of the preventive work safety relies on traditional procedures and not much work has been published focusing on the special problems facing workers during evacuation from these complex environments. However, a key factor for a successful evacuation from a construction site like a tunnel must acknowledge the importance of these procedural safety aspects. A typical problem that may occur in a tunnel construction site is the presence of several individually hired contractors, which may result in an unclear relationship of safety responsibility.

Still, the nature of the problems in the complex environments are similar to those in traditional assembly type buildings, i.e. there are problems getting aware of the fire threat, the cues related to fires have to be interpreted and a decision making process has to be initiated and finally there is a movement distance between the location of the people and a safe place. But, obviously there are differences, which are related to the increased complexity of the environment. Factors that may increase the complexity are:

- Visual access - limited visual overview, dim lighting, darkness etc
- Sound level - noisy environment, wearing ear protection
- Familiarity - poor knowledge of the environment, changing environment
- Physical conditions - obstacles and narrow passages, rough floor surface, slippery, drops, remote locations
- Work that need to be terminated properly due to safety reasons - drilling, blasting, welding

Even if not much focus have been on fire safety issues in tunnel construction sites there are a few reported fire incidents published. Some of these are presented in the main report in this research project, (Ingason, Lönnermark, Frantzich & Kumm, 2010). Much of the concern about fires occurring at tunnel constructions sites is related to the potential for large damages and the higher degree of difficult evacuation for the workers. Therefore an initial attempt to analyse the conditions for evacuating a tunnel construction site has been performed. This work is part of a larger research project, Fire incidents during construction work of tunnels, aiming at investigating fire safety in tunnel construction sites. The main report presents different aspects related to the fire scenarios and this report will focus on evacuation issues. Another part of the project deals with how to plan for an emergency response from both the tunnel constructor organisation and the local fire department, Kumm (2010). Results from the fire behaviour part forms an input to the evacuation analysis, which in turn is part of the conditions for the emergency response in the third part.

1.2 Objectives

The objective for the report is to identify certain aspects related to tunnel evacuation which are typical for the construction phase. The report will also present a mathematical method which describe the evacuation situation for workers exposed to a fire and evaluate the safety aspects for various tunnel configuration using this method. Finally, conclusions will be presented on how to arrange a tunnel construction site in order to facilitate a safe evacuation based on the results from this analysis.

1.3 Method

Data was collected from visits of tunnel construction sites in Sweden and attention was on evacuation related issues. An evacuation drill was performed in a Tunnel Boring Machine (TBM) to investigate the evacuation conditions for the workers and also to find out about evacuation and safety attitudes among these persons. This information fron the visits and the evacuation exercise was used to develop an evacuation simulation model in the Matlab framework and using this a sensitivity analysis was performed for different tunnel configurations and for different fire scenarios which were results from another part in the research project. Additional calculations were performed, using computational fluid dynamics models, to determine situations where the developed Matlab model was insufficient. Finally conclusions were drawn based on the results from the analyses.

1.4 Limitations

The work presented in this report mainly cover evacuation safety analyses in rather simple tunnel systems. A tunnel system can have different characteristics from a simple drilled hole into a mountain to a complex network of tunnels, some of them maybe already taken in operation. But in order to have a manageable set of typical problems to solve a decision was made to focus on the simple tunnels. Many of the results and conclusions are though still valid also for more complex systems.

Another limitation of the work is that no decision is made concerning what is an appropriate design fire. The objective is rather to investigate the outcome of different fire characteristics and not to provide a design guide for the user. The material can, of course, be used for design purposes but the level of safety is not the issue, which in turn will lead to a rational choice of design fires. Such a work will also imply the choice of design method, deterministic or probabilistic, but that is a completely separate task. Given the safety level the report can assist in providing recommended design of a tunnel.

A final limitation is that the tools used for the analysis need to be further validated. An evacuation safety tool was developed in the project but only the components in the model have been validated but not the combined effect of them. A further analysis should therefore be made in order to determine the model uncertainty when using the model.

2 Tunnel construction site evacuation

2.1 Introduction to tunnel evacuation

As mentioned in the introduction there are a number of issues relating to evacuation from construction sites that differs compared to evacuating from for example a building. Therefore attention has to be taken to plan for an emergency evacuation and to address these issues. But evacuating from a tunnel construction site is very much depending on in which phase of the construction the tunnel has reached. There are basically two phases; before and after the breakthrough point. Before this point in time the tunnel has only one entrance and exit; i.e. it is basically a long tube into the mountain. After the breakthrough there is a possibility to access the tunnel from at least two ways also permitting evacuation in two directions.

During the first phase the conditions for evacuation is almost the same over time. The physical conditions do not change dramatically as the site has a rough environment when the rock is excavated or drilling is taking place. The most important change in the conditions is the continuous increase of distance to the exit from the most remote part of the tunnel. After the breakthrough the work goes into another stage and drilling, blasting etc. is not that frequent. The work becomes more similar to a traditional building site with installation work and a cleaner environment. The type of work personnel also change from traditional tunnel excavating staff to persons not so familiar with tunnels as they also perform work on other construction sites for example in buildings. The awareness for the problems associated with an underground construction can therefore be assumed to be different.

However, as the work comes into a stage with more than one evacuation option the possibility for a successful evacuation is increased. In the first phase the only available escape route is the excavated tunnel i.e. the way back through the tunnel to the outside. A possible issue to handle is then that the distance to the safe place, which mostly is assumed to be outside the tunnel, can be significant. In cases with extremely long distances to the tunnel entrance a refuge chamber can be used. A refuge chamber is a protected, movable room equipped with breathing air and communication equipment. The procedure in a case of a fire is to evacuate to the refuge chamber and wait until the fire has extinguished or to be brought out by a rescue operation. In cases where parallel tunnels are constructed an escape route can be through a connection between the parallel tubes.

In the case the tunnel has a large cross section and there are long distances to the tunnel entrance the normal means for transportation is by car or a small train to reach different locations in the tunnel. Therefore there may be a possibility to use also the same car or train for evacuation in the case of a fire. It may though be a difference in accessibility comparing a car with a train as the train usually performs a number of tasks during a day and may not be available in case of a fire. Persons using a car often park the car close to the place of work will provide a better accessibility to the vehicle in case of an evacuation. It may, though, not be possible to evacuate using a vehicle if the fire is between the tunnel entrance and the location of the vehicle, it may then not be possible to pass the fire.

In order to increase the possibility for a safe evacuation most tunnel construction sites urge the workers to have direct access to a simple breathing apparatus, a mask with a small compressed air bottle or simply a filter mask. Using this equipment it can be assumed that movement distance through dense smoke can be extended.

Most tunnel construction sites are also equipped with other fire safety measures like a fire alarm, an evacuation alarm, means for communication, emergency lighting and way-guiding signs. The design of this equipment differs from site to site and no general recommendations are provided. In Sweden The Swedish Work Environment Authority issues regulations for work in underground sites, AFS 2010:1 (2010), mainly applicable for mines but can also be used for tunnel construction sites. They require a minimum level of safety equipment and how the fire safety issues shall be organised. They do, however, not provide detailed regulation on for example distances between alarm call buttons but state that this should be done in a sufficient manner. In this way the safety equipment can be organised according to the risks on the different sites.

Another important aspect with tunnel construction sites is that they often are interesting places for others than the workers to visit. Groups of external visitors are sometimes allowed to visit the construction site to see how the society is developing. The visitors could be the general public or certain groups like decision makers or members of various organisations. These people may have different needs in the case of an evacuation and usually guides from the construction company accompany these visitors. But still, there might be an increased risk due to a larger number of persons with limited evacuation capability. Also, these groups may travel by buses, which may increase the fire load in the tunnel. In cases where visitors are allowed on the construction site this problem cannot be neglected.

Many of these general aspects on evacuation safety are relevant for both phases in the construction, however, more predominant in the first phase. Therefore, most of the attention in this report is on the initial phase. Many of the problems in the second phase is also similar to those in tunnels taken into use. Differences do exist depending on the degree of completeness of the tunnel work but basically evacuation is don in the same manner and with a similar strategy.

2.2 Physical environment

Generally, the environment in a tunnel during construction is rather rough. The environment is characterised by low illumination, wet surfaces, uneven and sometimes slippery ground, on-going construction work with partly finished constructions, noisy and mostly a constantly changing appearance of the environment. This is of course a result of the places being a construction site but it will at the same time make evacuation more difficult. To have a work environment that is appropriate for the workers to stay in most tunnels are equipped with a forced ventilation system that delivers fresh air to each work place from where the tunnel progress in length. This results in an air draught towards the tunnel entrance, which also will govern the smoke flow during a fire. The fresh air is transported in a flexible textile tube beneath the ceiling.

Comparing the tunnel construction site with construction sites for traditional buildings reveal small differences apart from the tunnel being inside an enclosure. The most important factor with respect to evacuation is however the long distance from a working place in the most remote part of the tunnel to the tunnel entrance. This distance can in some cases be several kilometres. It is therefore important to have a pre designed plan for how to handle an evacuation and to have proper technical installations in the tunnel to make the evacuation safe given the conditions. A problem is that in many cases proper recommendations about the need for installations is lacking but mostly technical installations do exist, however, with little knowledge of the benefits of the installations and whether or not it is sufficient for the specific situation. Perhaps it is not very important to regulate for example the distance between illumination points in the tunnel but rather the fact that the illumination points shall be equipped with emergency power supply.

The environment is different depending on how the tunnel is excavated and two types of techniques can be identified; a tunnel being excavated using a blasting technique and a tunnel being excavated using a tunnel boring machine (TBM). There are also other types for example cut and cover tunnels but those do not pose the same problems for evacuation compared to the two first identified, mainly because of the length of the tunnel and the first two are enclosed.

Even if the tunnel is excavated with the use of a TBM some parts may still use the traditional blasting technique to do some constructions so both types may exist at the same construction site. Generally the environment is perceived more clean in a tunnel being constructed with a TBM as the constructed part of the tunnel often is similar to the appearance of the finished tunnel with wall elements and good walking paths along the tunnel. The TBM itself is somewhat different as it is a huge mechanical construction often with several floors connected by stairs. But as the machine is a fixed construction, but slowly moving, it can be easy to prepare it for an evacuation situation for example providing it with an evacuation alarm and way guiding signs. It is more difficult to provide a continuous way guiding in the blasted tunnel as these systems have to be expanded as the work progresses.

The following aspects characterise the tunnel environment with respect to evacuation:

Physical movement conditions

- slippery surface
- uneven or sloping surface
- height differences
- holes, banks, water basins inside the tunnel
- rail tracks
- long walking distance
- narrow passages (mainly for a TBM)
- use of vehicles for movement

Visibility

- low level illumination
- coloured light
- poor visual overview

Noise

- high levels during operation and blasting

Equipment and constructions

- excavating equipment parked in the tunnel
- storage in tunnel

Communication

- difficult to transmit radio communication
- traffic by cars, trucks and other equipment
- changing environment as work progress
- wayfinding issues (orientation problems, way guiding signs becomes covered by dirt)

In some way all these factors affects the possibility to evacuate safely. Depending on the type of construction method, the size of the tunnel cross section and the possible fire hazards, they are differently important for different tunnels. But generally most of them have to be handled in order to have a fast response by the workers and others occupying the construction site. One thing that is not mentioned is that the tunnel gets filled with black smoke in the case of a fire, which will make the actual evacuation difficult. The smoke will follow the fresh air supply in the tunnel and the evacuation of smoke is depending on the forced ventilation being able to maintain the operation in the case of a fire. In chapter 7 solutions to some of the factors will be further discussed.

2.3 Management aspects

Many of the problems related to evacuation safety can be handled with management procedures. In fact it is most important to have good procedures to be able to handle a fire situation and to be prepared for the occurrence of a fire. One of the major causes for management problems is the use of different constructing firms working at the same tunnel project and having them to cooperate in safety related issues. In many cases an infrastructure project like a tunnel is too large for a single construction firm to manage by itself so it is necessary to hire more than one. Usually the individual firms have been contracted to handle a certain part of the tunnel and when they can perform their work independent of other contractors the organisational issues are easily handled within the company. But when there is a physical connection between two or more contracts the management of the common safety issues becomes more difficult. This is a known problem in many large infrastructure works for example at the Norra Länken in Stockholm. Therefore, safety issues like simple ones such as the choice of radio communication systems must be solved before the contracts are signed.

Another management problem related to communication is the language problem. A tunnel construction is usually performed with people from different countries and with different backgrounds. People can in some cases not communicate in a common language and have to rely on key persons interpreting. This problem may occur both within a construction firm working isolated from others and when a break through has taken place and there is a physical connection to another contracted firm.

One interesting aspect that can be associated with management factors is the attitude among the workers with respect to safety issues. It can be assumed that the attitude can vary between individuals and between construction firms. There may also be differences with respect to the two main construction types, i.e. if the tunnel is excavated by traditional technique or by using a TBM. The attitude among TBM workers was investigated during an evacuation drill at the Hallandsås tunnel site and the findings are further described in a following chapter 4. But at that site the workers were highly aware of safety issues and felt them important. After visits at other construction sites the impression have been that the attitude related to safety issues can be more relaxed. This can, however, not be confirmed by any investigation.

The relaxed attitude among some workers may be related to the time spent in the tunnel and to previous knowledge of tunnel work. It is then believed that people not very familiar with tunnel work, for example sub contracted truck drivers, feel rather safe being inside their vehicle and maybe not so prone to follow stated regulations compared to persons having knowledge of tunnel construction. This is a problem that has to be dealt with in the case when planning for the work operation. It is, however, not investigated further in the report, part from the case at the Hallandsås tunnel site.

In order to increase the awareness about fire safety it is believed that evacuation drills or exercises are important. By participating in drills people get used to the idea about behaviour and conditions in the evacuation situation. But it is also believed that in order to benefit from the time and money spent by an evacuation exercise it must be adequately planned and performed. In some cases the exercise may only be seen as something necessary to do to be able to check a box in the management system. That must be considered a waste of both money and time. To get a successful result the evacuation exercise shall have a clear purpose and shall preferably be done as an uninformed evacuation where the persons subjected to the exercise are not aware of the exact time or the design of the exercise. A check-list for planning an evacuation exercise is presented in Appendix A. Another type of evacuation exercise is to perform it more as an education where the objective is to inform about the safety arrangements but both sorts of exercises are normally necessary.

A fire safety measure that is important during an evacuation is how to communicate with in the construction site and to the outside in the case of a fire. In many cases English is the language that shall be used but in the stressful situation this procedure may be neglected (Hallandsås). It is usually of most importance that correct information is given to persons within a tunnel system for a correct action to be taken by those who are not close to the fire.

As indicated in this chapter there are a number of management aspects that has to be addressed in order to have a safe tunnel construction site. The rest of the report will explore some of these aspects and also evaluate safety in tunnels under construction.

3 Previous studies

3.1 Accidents

Much of the work related to tunnels and evacuations in the case of fires are related to the completed tunnel, i.e. when the tunnel is in operation. This means that the special factors relevant for the construction environment have virtually not been investigated. However, some investigated issues are relevant for both the construction environment as for the completed tunnel but not much work has been published related to the environment this report focuses on.

Previous studies about fire safety issues during the construction of a tunnel are mostly results from fire accident investigations. Investigations have been performed for example after the fires in Store Baelt in 1994, the A86 fire outside Paris in 2002 and the Zürich-Thalwil fire in 2000, all described in Ingason et al. (2010). The main results, which are relevant for evacuation from these fires, are that the workers seem to be aware of the fire procedures as not many have been hurt and attempts to fight the fires were usually made. If evacuation was performed it was done in dense smoke. Other information about detailed activities among the workers is seldom reported.

3.2 Evacuation research

In the literature experiments on evacuation capabilities have been reported for tunnels already in use. The experiments have mostly used partly informed test persons but provide some interesting findings, which are applicable also for tunnels during construction. In Frantzich (2000) an experiment in a subway tunnel was performed. The test persons evacuated from a train, stopped in a tunnel, and evacuated to the nearest station. The walking speed was observed and a conclusion was that the walking speed was slow in the beginning, close to the train, but increased up to 1,4 m/s, as the persons became custom to the surface structure. The surface was a traditional track surface with rails and small stones, i.e. a rather difficult surface to walk on. The experiments were also performed in darkness so the situation is similar to evacuating in smoke, however, without the irritancy effects present.

Jin & Yamada (1985) has performed the maybe most well known results on walking velocities in smoke, figure 1. According to his findings the velocity differs between irritant smoke and smoke not that irritant. The velocities are presented as a function of the smoke density.

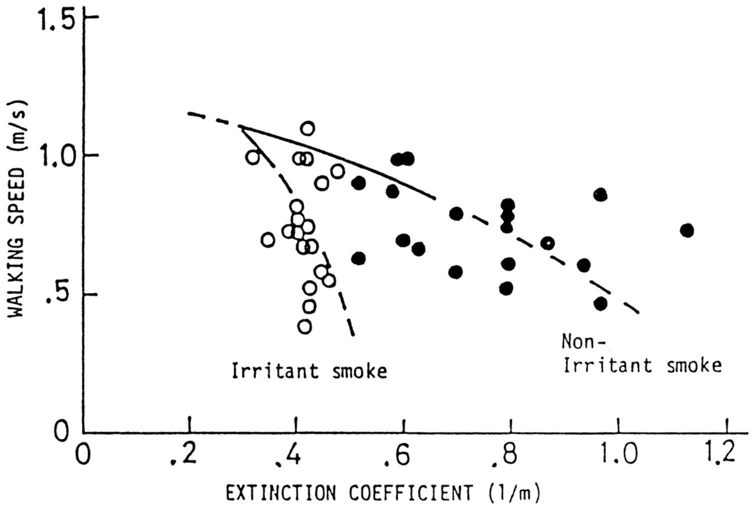


Figure 1. Walking velocity as a function of smoke density (Jin & Yamada, 1985).

A similar study was presented by Frantzich and Nilsson (2003) who conducted evacuation experiments in a short tunnel using irritating artificial smoke with a high obscuration, i.e. a low visibility. A direct comparison between this study and data by Jin & Yamada (1985) was not possible as the visibility conditions were not the same. However, the persons in the latter study showed a higher walking velocity despite low visibility. An important finding form the study by Frantzich and Nilsson was the test persons' tendency to seek guidance on direction from the tunnel wall. This may explain the higher velocity compared to Jin & Yamada. A significant difference was found between those test persons who followed the wall and those who did not, figure 2.

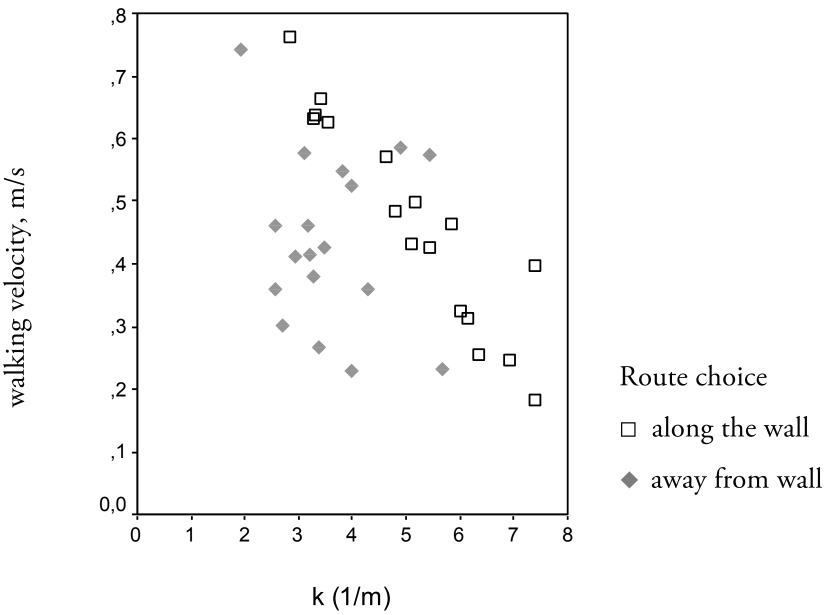


Figure 2. Walking velocity in irritating smoke as a function of smoke density for persons following the wall with the hand and for those walking away from the wall.

In many tunnels under construction a fire alarm is used to inform about a fire to those not close to the fire. Research has been performed to determine an appropriate form of the signal for the alarm. In public locations like assembly buildings, sub-way stations and similar a voice message has been proven successful (Frantzich, 2000; Proulx and Sime, 1991 and Frantzich, Nilsson, Kecklund, Anderzén and Petterson, 2007). In a tunnel under construction a simpler alarm like an alarm bell may be appropriate as the persons at the workplace can be educated about the meaning of the signal. Experiences from evacuation experiments at places of work indicate that using alarm bells in combination with training can make people start their evacuation very rapidly (Nilsson and Frantzich, 2007).

In some tunnel workplaces way-finding can be a problem and proper signage must be provided. This is most obvious in tunnels in the second phase of construction, i.e. when the break-through has taken place and several ways for evacuation are available. Nilsson and Frantzich (2007) have presented methods for improving the information needed for way finding by introducing flashing lights at the emergency exit signs, figure 3. This may be an appropriate means for places of work where the sound level is high making hearing a fire alarm difficult.

Figure 3. Illustration of equipment used by Nilsson and Frantzich (2007) to improve visual awareness of emergency signs.

Modelling of tunnel safety issues has also mainly been performed on the tunnel in operation, e.g. Bergqvist, Frantzich, Hasselrot & Ingason (2001) and Ingason, Bergqvist, Lönnermark, Frantzich & Hasselrot (2005) looking evacuation aspects in rail and road tunnels. The results indicate that motorists and passengers need an early notification and if the evacuation takes place in smoke the conditions for evacuating are difficult.

Evacuation research also involves the study of human behaviour in fires. This is a research field looking at the people's perception and actions in situations involving a fire or can involve a fire. Much attention has been put on studies on behaviour in public buildings and theories on human behaviour have been developed. The most acknowledged theories are the behaviour sequence model developed by Canter, Breaux and Sime (1980) and the theory of affiliation developed by Sime (1984).

The behaviour sequence model has been developed based on interviews and investigations after fire incidents. It claims to describe the human behaviour in terms of three sequence groups following each other; interpret, prepare and act. Each sequence group can include different actions which depend on the circumstances, i.e. not all actions are relevant for all occupancies and also the likelihood of them vary between occupancies. This theory can be used to explain certain behavioural patterns occurring or expected to occur in case of a fire. Modelling evacuation situations therefore need to consider the sequence of actions in order to fully understand the human behaviour implications.

The theory of affiliation developed by Sime (1984) and Sime (1985) acknowledges the familiar compared to the unfamiliar. In the case of an evacuation people tend to gather in groups or move towards familiar places for example moving towards the normal entrance of a building, i.e. usually the one they entered the building through. This behaviour has been seen in many cases and explains why people generally tend to use familiar escape routes and not necessarily the closest escape route. Key aspects in the theory are the role a person has in a certain circumstance and the formation of groups. In a tunnel in the construction situation the alternatives for evacuation are not many but there may be a choice between continue walking away from a fire or to enter a refuge chamber. In this case choosing the familiar will most likely be the expected choice.

A summary of evacuation research in tunnels may be found in Fridolf, Nilsson & Frantzich (2011) which applies human behaviour theories on a number of tunnel accidents. Finally, much of the evacuation research performed in ordinary buildings can be applied also on construction sites for tunnels, as the basic theories for human behaviour are general and not associated to a certain type of occupancy.

4 Evacuation from a tunnel boring machine

4.1 General assumptions

As a part of the present research project an evacuation drill was performed in a tunnel boring machine (TBM). The experiment took place in the future rail way tunnel in Hallandsås in the south part of Sweden. The TBM was at the time located approximately 5 km from the tunnel entrance and was more than half way through. The TMB is a two deck and 240 m long construction with a 10,6 m diameter drill head in front and a lining facility right behind the drill head, figure 4. The rest of the TBM consists of supply equipment for the drilling and lining activities. At the time of the experiment approximately 25 persons worked at the TBM and it was halted for maintenance work.

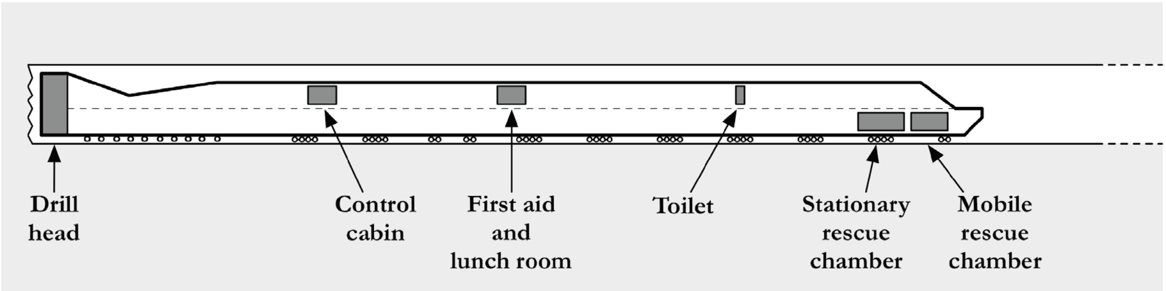


Figure 4. Illustration of the TBM seen from side. Total length is approximately 240 m, drill head diameter 10,6 m.

Evacuation from the TBM shall, in a first step, be done to the two refuge chambers located in the rear part of the TBM of which the most rear chamber can be driven away from the TBM along the tracks on the bottom of the finished part of the tunnel. The tracks are normally used by a supply train providing the TBM with element for lining the tunnel and other necessary equipment.

The purpose for the drill was to train the workers on the TBM and at the same time document the event for research purposes. Therefore, the TBM was equipped with more than 25 video cameras filming the important parts of the TBM, mainly places where the workers were supposed to be during the drill, the escape routes and the refuge chambers. The evacuation drill started when one in the experimental crew started manually the fire alarm. The alarm signal was an alternating tone signal. Due to safety reasons the TBM pilot were instructed to maintain in his normal location on the TBM. A full description of the evacuation experiment is presented in Frantzich and Nilsson (2009) and only a summary of the most important findings are presented in this report. In Kumm and Andreasson (2009) the complete fire drill is presented covering also aspects related to the fire services and management procedures by the construction company.

4.2 Results

4.2.1 Pre-movement time

Those tunnel workers visible on the video cameras responded within 30 seconds from the time the alarm started and most of them almost immediately.

4.2.2 Fire alarm

The fire alarm was perceived by all the workers. Most of them understood that they should evacuate and move towards the refuge chambers when they heard the alarm. All of them associated the fire alarm signal to fire, evacuation, danger and other similar.

4.2.3 Exit choice

Almost all of the workers used the walking paths normally used to access the different parts of the TBM, i.e. paths along the right side (seen from behind) of the TBM. As it is normally easier to walk on the lower deck many of the persons chose to climb down at the nearest stair to reach the lower deck and the refuge chambers which are located on the lower level.

4.2.4 Walking speed

The walking speed for the participant was rather fast at the point where speed was measured. In the stair the speed varied between 0,75 m/s and 1,0 m/s measured along the slope and the walking speed along a horizontal surface higher and ranged between 1,0 m/s and 1,7 m/s. The variation was low as most of the participants moved together in groups with almost the same speed.

4.2.5 Attitude

A key element in evacuation situations is the attitude towards fire safety issues and evacuation exercises. Therefore the questionnaire used in the investigation (Appendix B) contained a number of questions related to thoughts and knowledge about fire safety and similar.

It is clear from the answers that persons being alone or together with just one colleague were more uncertain about the situation than those who initially were sitting in for example the mess room. Persons being at other locations than the mess room and pilot cabin did to a higher degree associate the alarm signal to fire and emergency, figure C in Appendix C. People sitting together in the mess room could agree more rapidly that this is probably an exercise and not a real fire.

Notably is that all of the participants agree that tidiness is important and that safety procedures are important in order to keep a high level of fire safety. This indication of an articulated safety culture is probably one factor contributing to the rapid response to evacuate.

4.2.6 Evacuation time and general observations

The evacuation took approximately 3 minutes to perform from the time when the fire alarm started to all participants were inside one of the refuge chambers. The first participants arrived to the refuge chambers approximately 1 minute from the start of the fire alarm. The first ones to arrive started to prepare the mobile refuge chamber for the case they had to abandon the TBM and drive out of the tunnel. After this they entered the mobile refuge chamber.

A comment from the participants during discussions after the experiment revealed that communication between the participants on the TBM and between the participants on the TBM and persons outside the tunnel did not work properly. Communications over the radio during the experiment was sometimes in Swedish, which made it difficult for participants not understanding Swedish to follow the conversation. The formal procedure is that all communication shall be in English.

The participants also mentioned that there was a lack of information regarding the situation from persons outside the tunnel. As there was no clear sign of a fire at the TBM the situation was rather ambiguous for the participants when they were sitting in the refuge chambers. One person also mentioned that he was anxious that someone had not noticed the fire alarm and still be at a place in the TBM. The information about the exact number of persons on the TBM during the experiment was uncertain to the persons supposed to be the only ones at the machine.

4.3 General findings related to evacuation exercises

The fire exercise in Hallandsås showed good results regarding the benefits of practicing fire safety in tunnels. The outcome can be used to identify weaknesses and to find matters that can be improved for the case of a real fire.

In important factor for this useful result is proper planning of the exercise and to have a clear goal with it. When the goals are determined the drill can be planned, scenarios to examine can be described and the means for documentation can be determined. In the planning stage it must be determined what scenario the drill is supposed to simulate. Just arbitrary putting a smoke generator in a tunnel and wait to see what happens is a waste of time, money and trust. The reason for a proper planning is that the drill shall be beneficial both economically and in terms of improved safety.

It may be a good idea to document the exercise in order to provide a good feed-back to the persons participating in the drill and it is recommended to use video cameras. In order to quantify the benefit of training a questionnaire can complement the use of video recordings. The questionnaire can then be distributed to the participants just after completion of the evacuation drill and using the same questionnaire in all evacuation drills can provide an indication of the current evacuation status in the construction project. An example of a questionnaire can be found in Appendix B which is the one used in the evacuation of the TBM in the Hallandsås tunnel.

After the evacuation drill is performed and the questionnaires are collected it is preferred to have a general meeting with all the participants. This meeting has two purposes; to collect the response from the participants that they did not state in the questionnaires and second to act as a de-briefing session where participants can discuss more freely about their feelings during the exercise. This meeting after the drill can also be in smaller groups and be directed by an experienced interview leader. The meeting will then be seen as a focus group meeting, which is a formal way to gather viewpoints from different situations.

Finally, the participants shall be given information about how to deliver additional information they may share but which may be recollected a period of time after the exercise.

5 Conditions affecting the evacuation

5.1 Contributing factors

It would be useful to identify all possible scenarios that might be worth considering for an evacuation analysis. However, this is an impossible task as the number of possible outcomes is huge. But still, there is a need to find some of those that can occur during the construction of a tunnel.

The most obvious factor affecting the scenario is whether or not the fire occurs before or after the break through of the tunnel work. As mentioned previously in the introduction the evacuation situation changes drastically if there is more that one evacuation exit to choose between. Before the break through the only available evacuation route is the tunnel being constructed.

The second factor that may contribute in the scenario selection is related to the size and the shape of the tunnel system being constructed. If the tunnel simply is a long dead-end tunnel way finding problems are much less compared to the case where the tunnel is part of a larger network structure. Orientation aspects may in the latter case be a problem during the evacuation as the evacuees may end up in another part of the system instead of heading towards the tunnel entrance. A tunnel with larger cross section is assumed to be less hazardous as the radiative feed-back from hot smoke is less important and the smoke will be more dilute compared to a tunnel with small cross section. Also the length of the tunnel system affects the possibility for a successful evacuation.

Thirdly, evacuation depends on where the fire is located with respect to the persons being subjected to the hazard and what type of fire that can be expected. A fire with a rapid development rate and high peak heat release rate can be assumed to be more difficult to handle compared to a more slowly growing fire. Similarly, a fire close to the persons being affected by the fire increases the possibility that the fire is detected by the persons and possibly also extinguished. A fire remotely from the workers may trap them in the dead end part of the tunnel even if the fire is considered small because the hazard blocks the only escape route. This is of course only a serious problem in the case break through has not taken place.

Finally, the outcome depends on the capability of the persons supposed to escape from the fire. People have different capability to act in the case of an evacuation and the ability depends on a number of factors like age, gender, physical ability, familiarity of the environment, relationship to others in the occupancy and general awareness of the situation. The ability to act also depends on the environment i.e. how likely it is a fire or other signals of the fire are detected. Bad illumination, noisy environment makes it more difficult to be aware of the change in the conditions. On a construction site it is generally assumed that the persons subjected to the hazards are the workers on the site. It is though not unlikely, especially for a tunnel construction site, that also visitors from the general public may pay a visit. The visitors will most likely have less knowledge of the tunnel and may therefore be subjected to a higher risk as they are inside the tunnel.

All factors contribute to the outcome of an evacuation but not all of them are relevant in all tunnels. It is still necessary to consider them all together in terms of factors leading to different possible scenarios for analyses of the outcomes and to determine appropriate protection measures. The need for personal and other physical safety measures must rely on the analysis of what can happen in each of the possible scenarios.

The safety equipment used in tunnels under construction can be divided into three categories; personal protection, tunnel safety equipment and management procedures.

5.2 Personal protection

Typical protection equipment for personal use are any kind of breathing apparatus or filter mask, communication radio, flash lights and protective clothing. It is seldom possible to determine the exact benefit of each of these but all contribute to a rapid evacuation and possibly longer duration in a smoke filled environment. Using a filter mask will extend the distance a person can walk in a tunnel where there is a fire which in turn can lead to longer spacing between refuge chambers if such are in use.

5.3 Tunnel safety equipment

It is not possible to present a complete list of all protective measures that can be used in tunnels under construction. The reason is the constant development of new innovative solutions. However, some basic systems are more frequent than others. Typical safety equipment used in tunnels are automatic or manually initiated fire alarm including an evacuation alarm, normal and emergency lighting, prepared evacuation routes, smoke extraction or pressurisation systems for smoke management, refuge chambers, emergency vehicles, fire extinguishing equipment, vehicles equipped with extinguishing systems, transmission systems for radio and mobile phones, way guiding signs and access control systems. Another important installation is the air supply system providing fresh air to the construction locations. It may initially not be seen as a fire safety issue but it has a great importance for the spread of smoke in the tunnel system. For the tunnel constructor it is therefore important to know what should be done with the ventilation in the case of a fire, i.e. should the ventilation be turned off or shall it continue to provide air to the tunnel.

The benefits of these safety equipment depends on the system but can either provide early awareness of the situation, assist during evacuation or make it possible to reduce the number of evacuation occurrences.

5.4 Management systems

Construction of a tunnel is very regulated and worker safety issues are considered important. In Sweden The Swedish Work Environment Authority issues regulations on for example the need for a systematic approach in work safety. It is, however, the contractor who is responsible for the safety of the workers. The contractor has to prepare a management plan on how to handle safety issues during the construction phase. The authority's responsibility is to determine whether or not the contractor fulfils its responsibility, not to take over the responsibility from the contractor.

This means that routines and procedures, defined in the management plan, have to be implemented in order to provide with a good working environment. Management issues can for example be procedures on how and with which frequency evacuation drills are conducted or what type of vehicles or construction materials are allowed in the tunnel. The first one is supposed to improve evacuation capability and the latter to reduce the likelihood of fires. Other typical management issues are access control, fire intervention plans and hazardous materials location plans. The management plan must also be regularly checked so the intentions are met. This control function can for example include tests of the safety equipment, review of vehicles inside the tunnel system and workers health control. Also the evacuation drill can be seen as part of the control function.

It also is assumed that a continuous review of the management system is needed to avoid degradation. It is possible that this review is more important for the management system compared to the other two protection categories, but that has to be verified in a future work.

5.5 Evacuation scenarios

The basic difference for the outcome of an evacuation is caused by whether or not the tunnel is a tube with openings in one or two directions. In the case of two openings in the tunnel there is always a possibility to evacuate from the fire and reach a safe position even if there may be situations where the evacuation has to take place in smoke. But before the work has progressed to that situation there will only be one possible escape route to the tunnel entrance. Depending on the type of tunnel system the evacuation situation can be improved by for example the presence of a parallel tunnel tube and connections between them. Still, there will be parts of the tunnel with only one option for evacuation. In order to improve the evacuation situations a refuge chamber may be used in which the tunnel workers can seek shelter in the case of a fire.

Looking at the case where the break through has not yet been reached there are a number of different scenarios that can occur depending on the factors described above. These fundamental evacuation scenarios describe the situation for tunnel workers and depend on the different locations of the workers, the fires and the safe locations, i.e. the refuge chamber or an evacuation route to a parallel tunnel tube. Generally, evacuating to another tunnel tube can be assumed to be equivalent to seeking refuge in a refuge chamber even if the two tunnel tubes merge into one room or tunnel tube further down the tunnelling system.

These fundamental evacuation scenarios, A - C, can be analysed in terms of person safety and be used for providing recommendations on how to manage a fire from a administration point of view. The most important information is to provide information on how to manage the ventilation system but also other recommendations can be concluded from this analysis e.g. the location of the refuge chamber, the type of alarm system etc. In each of the fundamental scenarios two locations of persons will have to be examined; persons located in the most remote part of the tunnel and persons somewhere between the place of work, i.e. the most remote place, and the tunnel entrance.

In the main report from this research project, Ingason et al. (2010) a number of fire scenarios were identified. These were denoted scenario 1 to scenario 12. The last four fire scenarios are, though, relevant only after break through has occurred. The main differences in the fundamental evacuation scenarios are where the fire is located with respect to the locations of the place of work and the safe location. It is, though, possible to create links between the fire scenarios in the main report and the fundamental evacuation scenarios. The fundamental evacuation scenario A corresponds to the conditions described as fire scenarios 1, 6 and 8 in the report by Ingason et al. (2010). These scenarios are characterised by a fire location in the most remote part of the tunnel system. The other fire scenarios are relevant for the two other fundamental evacuation scenarios. The differences within the scenarios are mainly focused on the type of fire and if the vehicle is moving or not. It is therefore, relevant to distinguish between the fire scenarios and the evacuation scenarios to be able to capture the importance of the governing variables for both the fire development and the evacuation outcome.

5.5.1 Fundamental evacuation scenario A

This scenario, figure 5, assumes that the fire is located in a drilling rig or similar located at the place of work. The persons in the tunnel can only move in one direction, i.e. towards the tunnel entrance. Depending on when the evacuation is initiated the persons have to aim for an evacuation route or a refuge chamber between the work place and the tunnel entrance. In other cases they may continue the complete distance to the entrance. As the fire is located close to the work place there will be no problem with the fire destroying the air supply tube. As long as the air supply is running the smoke will move towards the tunnel entrance with the same velocity as the air supply. Persons located at two positions, A1 and A2, have to be included in an analysis for evacuation safety.

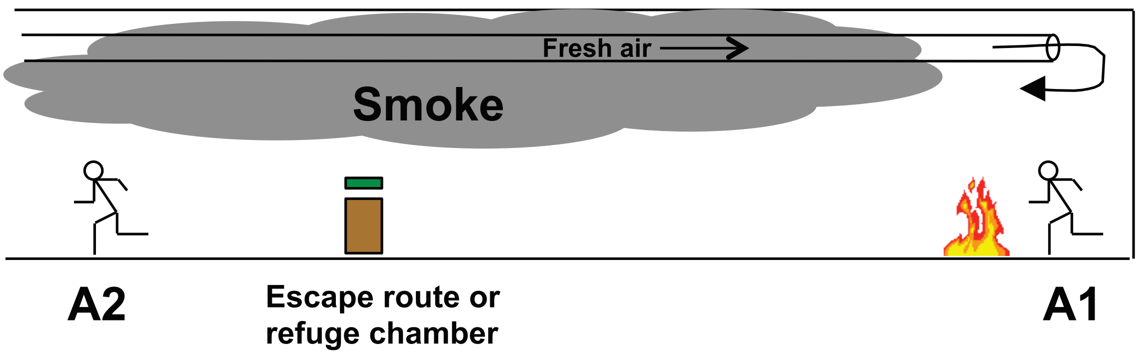


Figure 5. Fundamental evacuation scenario A with two locations of the persons, A1 and A2.

5.5.2 Fundamental evacuation scenario B

In this scenario, figure 6, the fire is located away from the place of work and is for example caused by a car accident or a fire in stored goods. The fire does not directly block the way between the most remote location and a safe place. When the fire starts the persons working in the tunnel must be notified of the fire as it may not be visible at a distance. The fire can also cause a rupture in the tube for the air supply changing the smoke movement conditions. As long as the air supply is running as normal the smoke will move towards the entrance and persons further into the tunnel compared to the fire location can move towards the escape route or to the refuge chamber. Also, in this scenario, persons at two locations, B1 and B2 have to be considered in a safety analysis.

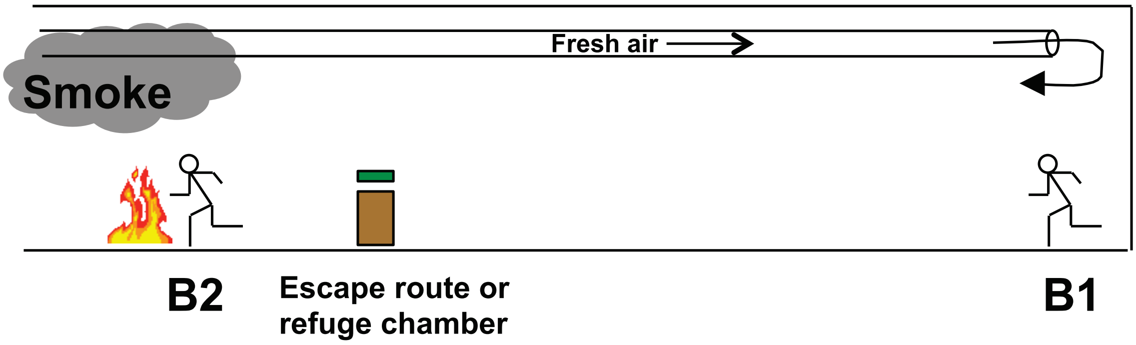


Figure 6. Fundamental evacuation scenario B with two locations of the persons, B1 and B2.

5.5.3 Fundamental evacuation scenario C

This scenario, figure 7, has similarities with scenario B but the fire is located between the persons at the workplace in the tunnel and the safe place, i.e. the escape route or the refuge chamber. As in scenario B the conditions for evacuation will change if the fire destroys the air supply tube. Before this the smoke will move away from the persons providing them with some possibility to reach the safe place in a smoke free environment on condition the can pass the fire which after a while will create untenable heat radiation levels.

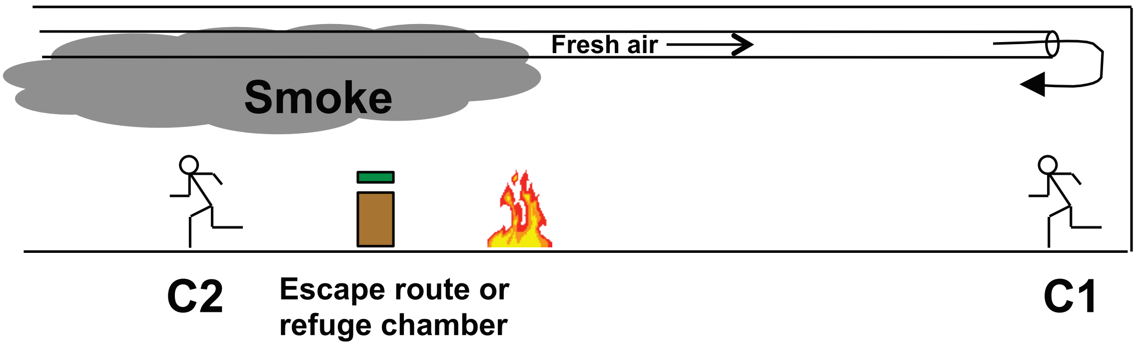


Figure 7. Fundamental evacuation scenario C with two locations of the persons, C1 and C2.

5.5.4 Evacuation analysis

In order to provide recommendations on how to make sure the tunnel is equipped with proper safety equipment all three scenarios have to be investigated including the different locations of the persons in the tunnel. The exact performance of the analysis has to be decided according to the current conditions but a general analysis can also be done giving the basic trends on how the conditions during an evacuation can develop.

The following chapter will provide some additional information by examining the possibility to evacuate a tunnel in the case of a fire. Two basic situations will be investigated; fire in the most remote location of the tunnel and fire in the middle of the tunnel destroying the air supply tube, i.e the fundamental evacuation scenarios A and B. Most effort will be on the first scenario while the latter will be investigated only in terms of smoke transport. The last fundamental evacuation scenario will, though, be treated slightly simplified. This scenario is similar to scenario B but the fire blocks the direct access to the safe location. The only aspect complicating the situation compared to the other scenarios will be the heat radiation levels from the fire making it impossible passing the fire. In chapter 7 a discussion will be made regarding the management of these scenarios.

6 Evacuation modelling

6.1 General modelling assumptions

It is not possible to perform an experiment for every evacuation situation that may occur. Instead a mathematical approach has to be used in order to investigate the consequences of relevant fire scenarios that can occur. There are a number of evacuation models available but not all of them can simultaneously handle both smoke spread calculations and evacuation calculations to have a result combining the two. Therefore, in this project a simple one dimensional Matlab model was developed to be used for a sensitivity analysis of the evacuation conditions for a number of fire scenarios.

This model was primarily used for investigating the consequences in the fundamental evacuation scenario A. It can, however, also be used for other situations e.g. persons at locations A2, B2 and C2 in the fundamental evacuation scenarios. But the analysis in this chapter assumes that the scenario to investigate is the fundamental evacuation scenario A.

The model is intended for the situation before break through and assumes there is a fire in the tunnel at the most remote position, i.e. the place where the tunnelling work is performed, figure 8. The fire is defined by the heat release rate (HRR), which express how fast the energy is released during the fire. The ventilation system supplying fresh air to the location of work is assumed to be operating during the evacuation time. The supply air transports the smoke away from the fire towards the tunnel exit. The supply air velocity is constant during the evacuation but is determined by the scenario conditions. As the model is one dimensional it is assumed that the smoke is evenly distributed across the tunnel cross section and the same conditions apply at all cross section points for every distance from the fire.

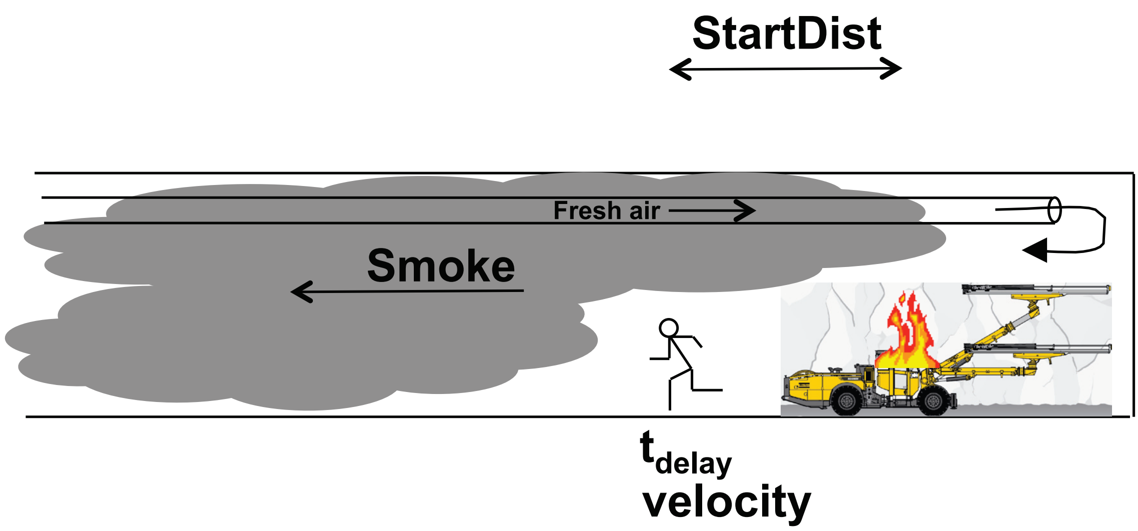


Figure 8. Schematic illustration of the modelling conditions.

The model assumes that people start their evacuation after a defined delay time and then move towards the exit. The persons are initially located at a short distance from the fire, Startdist. In most scenarios this distance is 50 m from the fire.

The reason for this approach is that it is assumed that the persons during the delay time respond to the fire cues and prepare for evacuation or tries to extinguish the fire, i.e. they are not evacuating. It is likely that they can perform these tasks without being severely affected by the smoke and heat from the fire.

It is further assumed that smoke close to the fire will accumulate beneath the ceiling and the persons will, therefore, not be exposed to any harm from the fire during the delay time or staying within the Startdist distance. As a consequence the model only assumes that the smoke is evenly distributed across the tunnel cross section after the distance Startdist.

The model attempts to describe the situation during the evacuation along the smoke filled tunnel, i.e. at the locations where the persons currently are located. A limitation with the model is that all smoke must follow the air stream. If a more complex smoke movement pattern is expected a more detailed smoke spread models has to be used.

As the persons in some scenarios move through smoke the walking velocity is determined by the visibility at the present location. The velocity is calculated using research by Jin (1978) and it is assumed that the smoke is irritating, which results in a more rapid decrease in walking velocity as the smoke density increases. In a well illuminated and smoke free environment it is assumed that the persons can walk with 1,4 m/s and in the worst smoke logged conditions the minimum velocity is 0,2 m/s which corresponds to movement in darkness.

The smoke spread part of the model predicts the concentration of CO, CO_2, O_2 and soot, and the visibility, temperature and heat radiation level at the locations the persons move to at each time step. This part of the model uses the expressions derived by Ingason (2005). This information is used to calculate the accumulated Fractional Effective Dose (FED), which is a measure of toxic accumulation due to smoke inhalation. The FED model used is developed by Purser (2008) and it assumes that persons become incapacitated, i.e. they are assumed to become unconscious, when the FED value reaches 1,0. The persons are then prevented from further evacuation but are still considered alive and will accumulate the toxic components but at a lower rate. They will continue to accumulate toxic components until they have reached a lethal dose of toxicity, Fractional Lethal Dose (FLD). The model by Purser can also be used to predict the time when lethal conditions are reached.

The results obtained from the model is basically the distance the persons can move away from the fire until they become incapacitated by the accumulated inhaled toxic components in the smoke and the time it takes until they reach FLD = 1,0, i.e. fatal conditions.

None of the persons are assumed to wear any breathing protecting equipment e.g. filter mask or breathing apparatus.

In the calculations with the model the following parameters are determined

- distance from the fire where the evacuating persons have reached FED = 0,3
- time from the start of the fire until FED = 0,3 for the evacuating persons
- distance from the fire where the evacuating persons have reached FED = 1,0
- time from the start of the fire until FED = 1,0 for the evacuating persons
- time from the start of the fire until FLD = 1,0 for the evacuating persons

The reason for calculating the parameters until FED = 0,3 is that this value often corresponds to a design value for the maximum exposure during evacuation. It can therefore be a rational level for determining the longest distance to the closest safe location, either an emergency exit or a refuge chamber. The exposure FED = 0,3 does provide for a margin of safety but it is used in other situations where calculation of evacuation is performed and can be used as a first assumption of safe conditions.

A detailed description of the equations used in the calculations is presented in Appendix D.

6.2 Choice of scenarios

In chapter 5 a number of factors were identified relevant for the selection of scenarios to investigate with respect to occupant safety in case of fire. These factors were:

1. construction phase
2. tunnel configuration
3. fire hazards
4. human related issues

It was decided in the research project that most attention should be on the construction phase before the break through. The results from there analyses can, however, be used to predict also the consequences after the break through if the conditions downstream from the fire is the issue.

What is missing following this assumption is the effect from backlayering, figure 9. Some portion of the smoke will move against the air current in the tunnel forming a smoke layer beneath the ceiling but that will not be predicted using the model for the break through phase. As most of the analysis in this report focus on a tunnel with only one opening backlayering is not an issue.

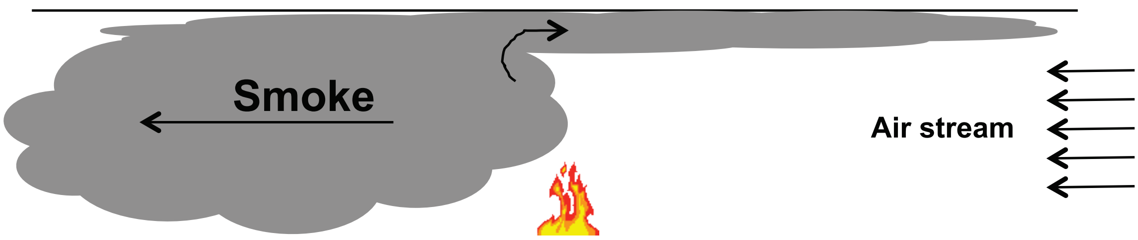


Figure 9. Backlayering effect in case of fire in a tunnel with two openings.

The tunnel configuration was identified as important for the safety of the workers; several cross section alternatives were investigated. A span of cross sections covering small wastewater tunnels to larger road tunnel alternatives were chosen, se section 6.3. The tunnel length will also affect the outcome of the analysis and the tunnel length was chosen to be 1700 m in all scenarios. This length is chosen to represent a long tunnel but otherwise the length is arbitrarily chosen.

The choice of fire hazards is most likely the variable affecting the results more than any other. One part of the research project focuses on the different types of fire scenarios possible in a tunnel under construction. This part has identified a number of vehicles that are used for construction purposes and four of these were chosen, section 6.4.

The last of the factors influencing the choice of scenarios is related to the persons working in the tunnel. It is assumed that most of the persons are aware of the conditions in the tunnel for example where the exits are located and how to move towards the safe location. Way finding is, therefore, assumed to be a small problem and the recognition and response time can be kept rather short. From the evacuation experiment in the TBM it can be assumed that the workers can respond rather rapidly but it is also assumed that they will try to extinguish the fire. Therefore, the recognition and response time will be longer than the situation in the TBM in Hallandsås. It is also assumed that the time to detect the fire is short and can be included in the recognition and response time. As the workers detect the fire by themselves none of the scenarios include any automatic fire alarm but the time to report the fire can be included in the recognition and response time i.e. the delay time before movement towards the tunnel exit. A further discussion about this factor is presented in sections 6.6 and 6.7.

As the model intentionally was developed to handle evacuation from a tunnel where the fire occurs at almost the same location as the persons evacuating focus will be on scenarios following this assumption.

6.3 Tunnel cross section

Five cross section sizes are chosen for the analysis, table 1. The choices shall represent different types of tunnels from the smallest wastewater tunnel to a multilane road tunnel.

Table 1. Tunnel geometry for the sensitivity analysis

Cross section, m^2	Area, m^2	Perimeter, m
3 x 4	12	14
4 x 5	20	18
5 x 5	25	20
6 x 7	42	26
7 x 11	77	36

6.4 Fire development

The sensitivity analysis will be performed using four different fire development curves

- blast hole drilling rig
- two cars
- articulated hauler
- bus

For some of the fire development curves alternative HRR-curves are used. This is done to determine if the development curves are close to result in a dramatic shift in the outcome. Figures 10-13 show the selected fire development curves, which are based on the analysis provided in Ingason et al. (2010). The figures showing the HRR for the four fire scenarios include heat release curves for some traditional t^2-fire curves for references. These curves were used for comparison in an extended sensitivity analysis where parameters affecting the shape of the four HRR-curves were varied. The curves are mathematically described in appendix D. In the figures the so-called basic fire development curves are marked with a blue solid line. The alternative curves are marked with other point symbols.

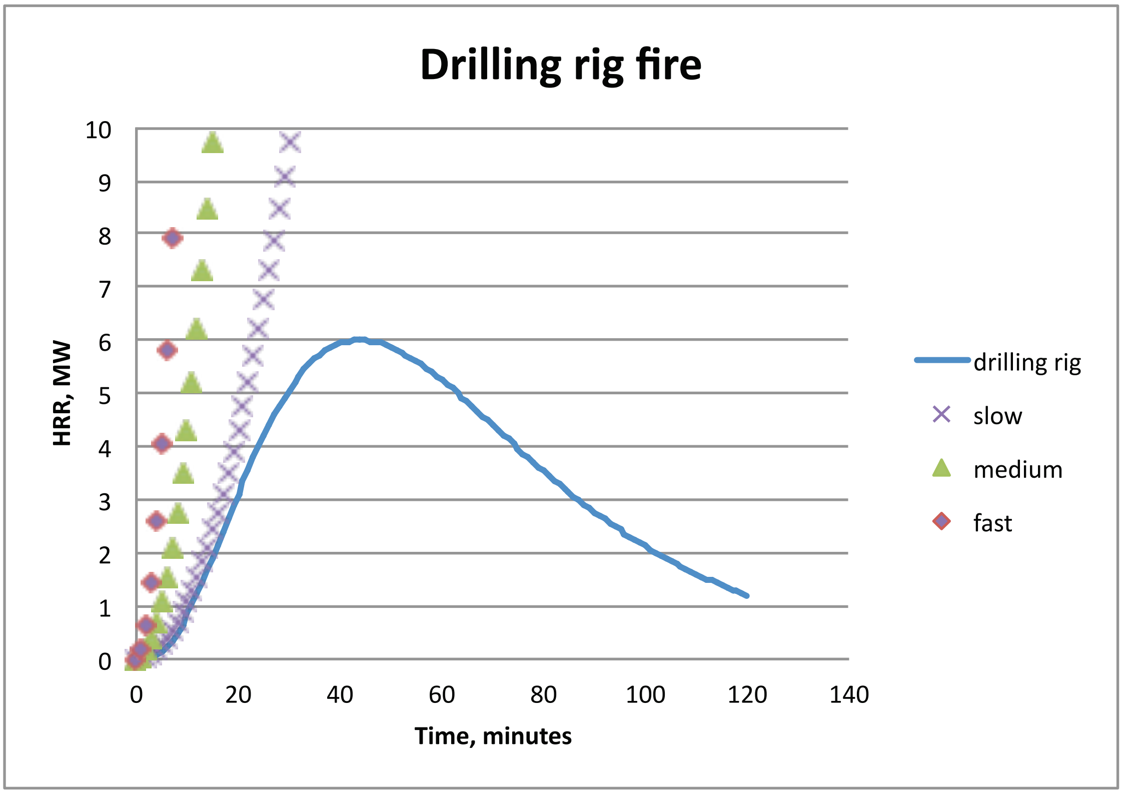


Figure 10. Heat release curve for a blast hole drilling rig (Ingason et al., 2010).

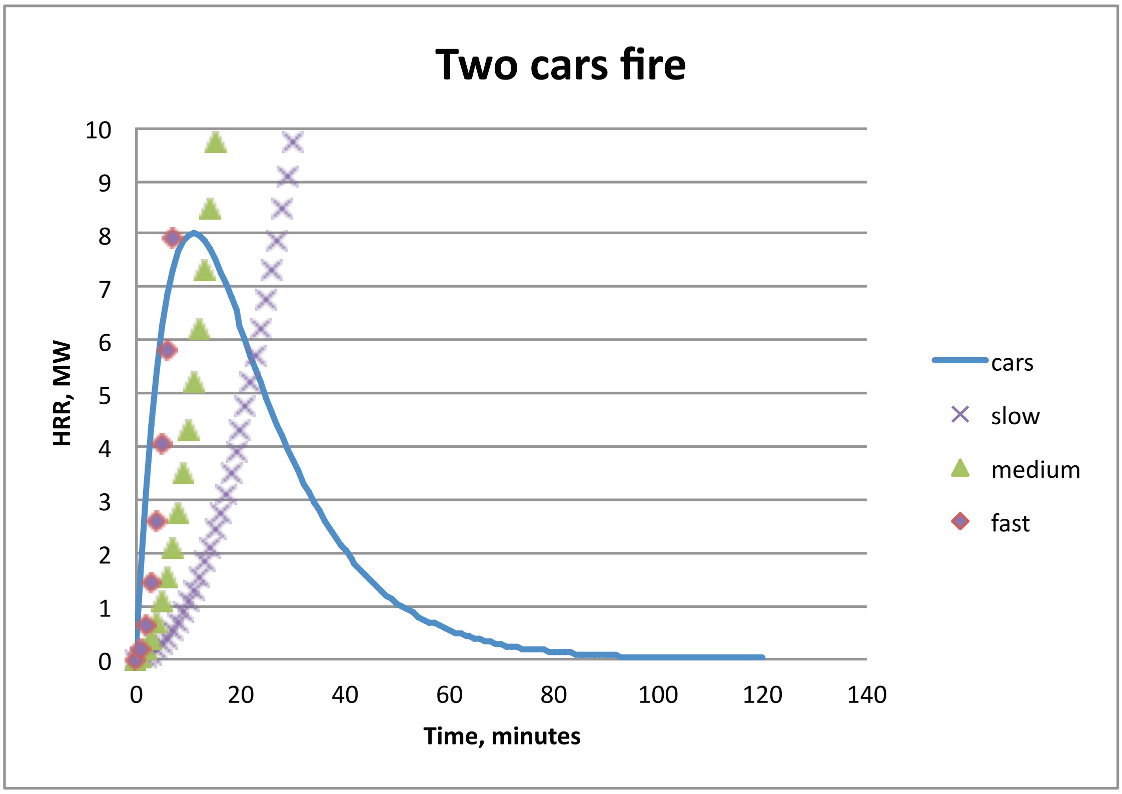


Figure 11. Heat release curve for two cars (Ingason et al., 2010).

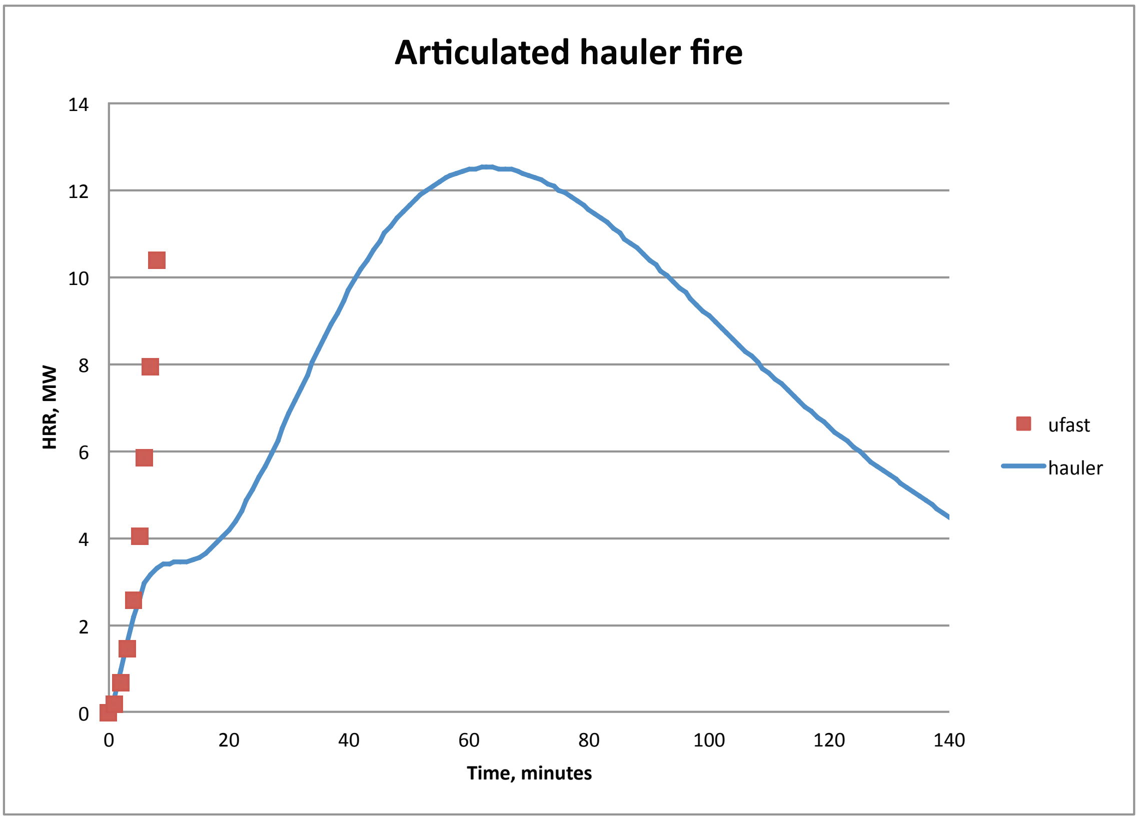


Figure 12. Heat release curve for an articulated hauler (Ingason et al., 2010).

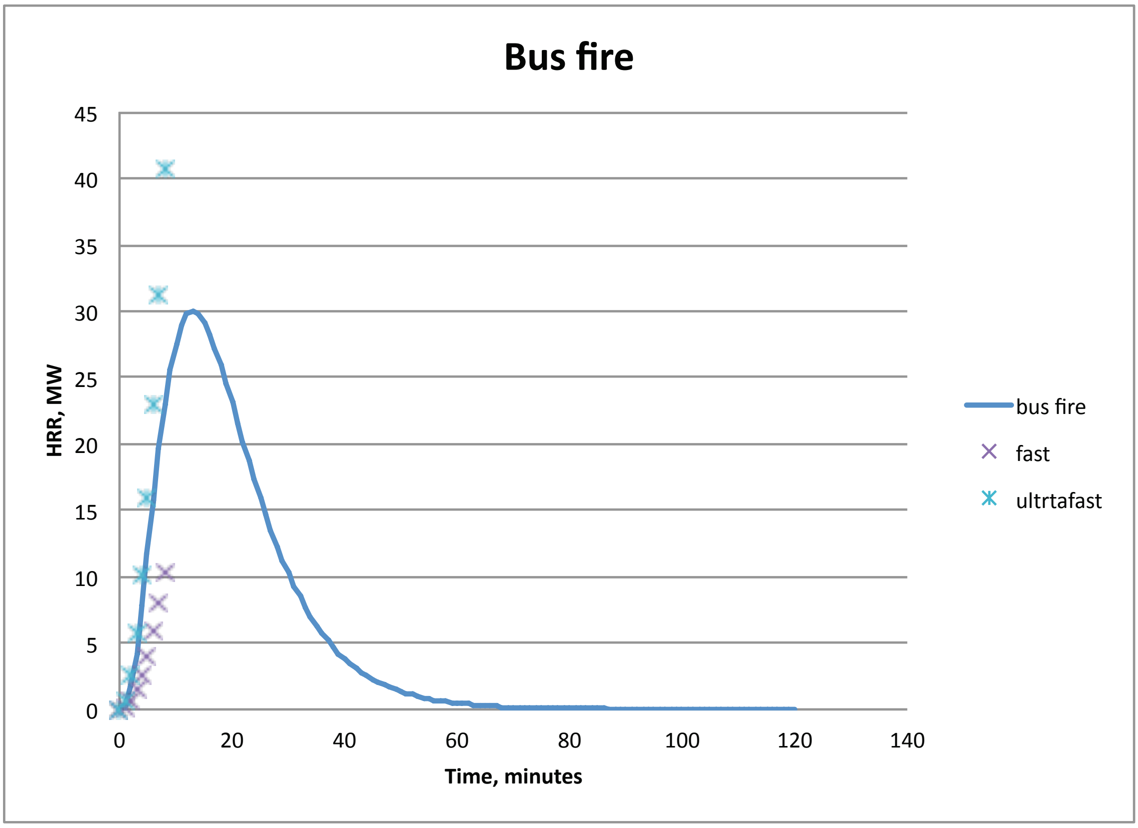


Figure 13. Heat release curve for a bus (Ingason et al., 2010).

6.5 Air velocity

In order to provide a good working environment in the tunnel air is constantly supplied to the different work places. Usually the airflow is designed to maintain a minimum air velocity perpendicular to the cross section at 0,5 m/s. The smoke will move with the same velocity. To investigate the importance of the air velocity also 1,0 was used, as higher velocity will result in a more diluted smoke providing a better evacuation environment.

It would be interesting to also determine the smoke spread conditions for supply air velocities lower than 0,5 m/s. But in that case gravitational forces determine smoke movement and the model does not include buoyancy driven smoke movement. It can, however, be assumed that the smoke movement velocity for that situation is lower than 0,5 m/s as the air movement in the tunnel is almost extinguished if no mechanical air supply is present.

It would be rational to assume a relationship between the fire development and the air velocity as a higher air velocity would result in a more rapid initial increase of the fire heat release rate. This correlation was, however, not considered in the analysis

6.6 Recognition and response time

It is important to recognise human behavioural aspects in the analysis but it is not possible to precisely determine sequence of actions, as that information does not exist. This is in contrast to for example public buildings where investigations from fires has been used to compile behaviour sequences (Canter, Breaux and Sime, 1980). However, it is possible to assume likely behaviour sequences for the persons working in a tunnel, applying the theory of behaviour sequences, based on previous experiments and visits made in the tunnels, which are included in this project.

The recognition and response time will most likely depend on previous training and other external conditions like the type of fire, the location of the fire, presence of others at the location of the fire, roles and responsibility factors for the persons in question etc. It is likely that the persons working in the tunnel will attempt to fight the fire if they are close to the fire. If they only hear a fire alarm they will leave the tunnel but most likely not immediately. A time delay for investigating the source of the alarm will follow the awareness of the signal. The persons will confirm with others before making the decision to leave and that take some time to do.

From previous investigations it is assumed that it is likely the delay time will be shorter if the persons are well trained and motivated to respond to fire related cues. It is likely that the persons try to move away from the hazardous zone and move towards a safer place for example e refuge chamber or an escape route. This is also in accordance with general behavioural theories, e.g. the theory of affiliation (Sime, 1984).

As the model developed is rather crude a detailed description of the behaviour sequence is not necessary. Instead the actions performed after being aware of the fire or hearing the fire alarm is combined into a time delay, i.e. the sum of the recognition and response time and the time to detect the fire. Also, during the evacuation a number of responses are likely but they are also all combined into this time delay.

Therefore, the behavioural aspects are treated by adding the awareness time and the recognition and response time to the movement time derived from knowing walking velocities in various conditions. The recognition and response time is based, as the name indicate, by an initial recognition phase where the cue is interpreted and a following action.

As the persons supposed to evacuate are close to the source of the fire it is assumed that the time to detect the fire is small. The delay time prior to evacuation is, therefore, only depending on the recognition and response time and the awareness time is assumed to be zero.

For tunnels under construction one can only guess what a likely recognition and response time could be, i.e. the time delay until the workers start to move towards safety.

A first estimation of the recognition and response time is therefore linked to the fire development. It is assumed that the workers start to move away from the fire when the fire heat release rate is 3 MW or maximum 5 minutes after the fire has started. A 3 MW fire is a rather large fire with flame height of more than four metres for a 2 m^2 fire. This fire is supposed to be difficult to extinguish and this alternative is, therefore, not relevant at that time.

The 5 minutes criterion is chosen because some of the fire development rates are very low. For example the drilling rig fire peaks at 6 MW after approximately 40 minutes and the 3 MW level is reached after 17 minutes. A maximum delay time was therefore assumed for cases where the workers leave even if the fire could be extinguished but no attempts were made or were not successful.

The recognition and response times chosen as initial values are presented in table 2. In the analyses other recognition and response times are also used as a part of the sensitivity analysis.

Table 2. Initial recognition and response times.

Scenario	Recognition and response time, minutes : seconds	Reason for the choice
blast hole drilling rig	5:00	max time
two cars	2:00	3 MW fire
articulated hauler	5:00	max time
bus	2:30	3 MW fire

6.7 Number of persons

As the purpose of the analysis is to provide an estimate of the level of safety in tunnels under construction the number of persons in the analysis is less important. Usually only a few persons are at the place of work and the analysis will therefore consider the safety for those. However, if the scenario considers a bus there will be a time delay if the bus has to be evacuated. In this scenario, it is assumed that all passengers are outside the bus and the bus itself will be the fire hazard, i.e. defines a likely heat release curve. The tunnel is large enough so a flow restriction of the evacuees is not assumed. Therefore the analysis can be seen identical for all individuals evacuating from the fire as they move as a group.

6.8 Results

The results from the analysis are presented in the following subsections. The results are presented as the five parameters defined in the beginning of chapter 6 for each of the input parameter combination examined in each fire scenario. The first three columns in each result table define the investigated scenario and the results follow. The calculations are made for a maximum time of 120 minutes. In cases where the FLD value did not reach 1,0 at 120 minutes the last column in the result tables instead contain the FLD value for the maximum time.

The first five rows in the tables, shaded, represent the basic assumptions, which are followed by calculations where one or more parameters deviate from their original values, i.e. the results from the sensitivity analysis. In Appendix E results from the complete sensitivity analysis is presented for the four fire scenarios. This sensitivity analysis also includes variation in other parameters for example the fire growth rate for some of the scenarios.

6.8.1 Scenario 1. Blast hole drilling rig

The scenario represents a low hazard scenario but drilling rigs are common in tunnels and therefore important to investigate. Because the fire development is slow the recognition and response time is chosen to 5 minutes according to above. The results from the calculations are presented in table 3.

Table 3. Results for the blast hole drilling rig fire scenario.

Cross section, m2	Air velocity, m/s	Rec&Resp time, min:sec	Dist to FED=0,3, m	Time to FED=0,3 or safe, min	Dist to FED=1, m	Time to FED=1, min	Time to FLD=1 or max FLD at 120 min, min or FLD
3x4	0,5	5:00	>1700	25	>1700	-	0
4x5	0,5	5:00	>1700	25	>1700	-	0
5x5	0,5	5:00	>1700	25	>1700	-	0
6x7	0,5	5:00	>1700	25	>1700	-	0
7x11	0,5	5:00	>1700	25	>1700	-	0
3x4	0,5	11:00	236	26,5	380	38,5	49
4x5	0,5	11:00	308	32,5	530	51	84
5x5	0,5	11:00	350	36	614	58,5	0,95
6x7	0,5	11:00	470	46	926	84,5	0,71
7x11	0,5	11:00	674	63	>1700	120	0,47
3x4	1	11:00	296	31,5	524	51	0,96
4x5	1	11:00	398	40	836	77	0,7
5x5	1	11:00	596	56,5	1118	100,5	0,65
6x7	1	11:00	677	60,5	>1700	120	0,4
7x11	1	11:00	1208	103	>1700	120	0,2

It can be seen from the table above that evacuating the tunnel in case of a fire in the blast hole drilling rig will be rather unproblematic. The reason for this is that it is only during the initial part of the evacuation that the persons are exposed to the hazards from the smoke and the smoke is very thin during this stage. They can therefore walk past the smoke front and during the most of the evacuation they move ahead of the smoke front, cf. figure 14.

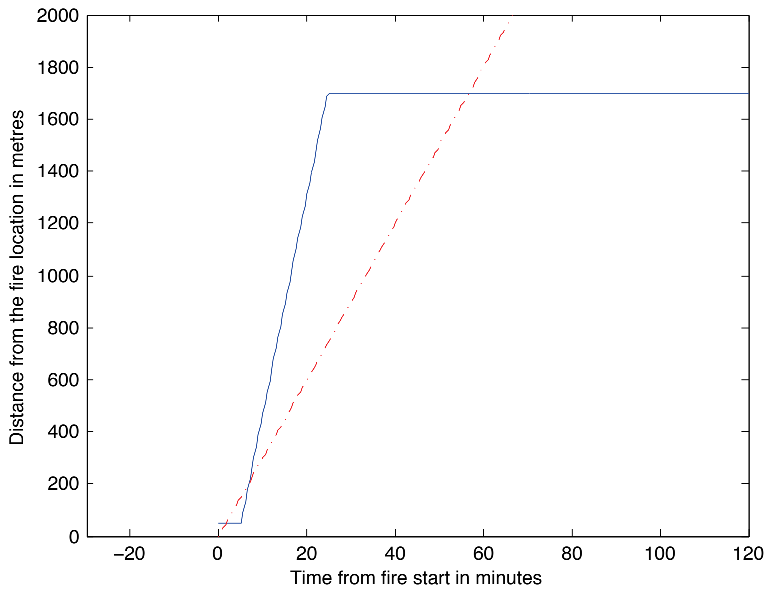


Figure 14. Location of persons (blue solid line) and smoke front (red hatched line) for evacuation in the 7 x 11 m^2 tunnel and 5 minute recognition and response time (last of the grey conditions in table 3).

The recognition and response time is initially chosen to 5 minutes, which was the maximum time based on an assumption about time to make an attempt to extinguish a fire. But the fire growth rate for the drilling rig is very low so it might be possible that the persons close to the fire tries to extinguish the fire for a longer period of time. Therefore, a longer recognition and response time was also used for the calculations, i.e. the cases with 660 second delay. This time represents the time it takes for the fire to grow to 1 MW which represent a fairly large fire.

Then the evacuation will be limited due to the inhalation of toxic smoke. For an air velocity of 0,5 m/s the distance to FED = 0,3 varies between 240 m and 670 m depending on the cross section. If it is possible to have a higher air flow in the tunnel the distances to the chosen criteria increase. But it is only for the largest cross section people can evacuate the whole distance to the outside, i.e. reach the distance 1700 m.

If the persons reach the level of incapacitation it is still possible that they can be rescued, at least if the tunnel cross section is large, i.e. the toxic concentrations are then lower. This is, though, only relevant for the cases where the time to start the evacuation is longer than for the basic assumptions.

6.8.2 Scenario 2. Two cars fire

The peak heat release rate for this fire is not much different compared to the previous fire. But the rate at which the heat release increases is much higher in this scenario where the peak is reached at almost 10 minutes from the start of the fire. This will have a major impact on the possibility to evacuate. The results from the analysis are presented in table 4.

Table 4. Results for the two car fire scenario.

Cross section, m2	Air velocity, m/s	Rec&Resp time, min:sec	Dist to FED=0,3, m	Time to FED=0,3 or safe, min	Dist to FED=1, m	Time to FED=1, min	Time to FLD=1 or max FLD at 120 min, min or FLD
3x4	0,5	2:00	116	7,5	164	11,5	13,5
4x5	0,5	2:00	152	10,5	248	19	72
5x5	0,5	2:00	176	12,5	314	24	0,8
6x7	0,5	2:00	242	18	680	55	0,66
7x11	0,5	2:00	398	31	>1700	-	0,38
3x4	1	2:00	146	10	278	21	0,82
4x5	1	2:00	206	15	>1700	0,95	0,61
5x5	1	2:00	254	19	>1700	0,74	0,47
6x7	1	2:00	458	36	>1700	0,41	0,26
7x11	1	2:00	>1700	83	>1700	-	0,14

This situation is more severe even as the recognition and response time is only 2 minutes. This is the time when the fire reaches 3 MW. But even if the persons become incapacitated there is a chance they can be rescued by others as it is only for the tunnels with smallest cross section FLD levels higher than 1,0 are reached. In most of the other cases the FLD curve flattens out as the fire itself is decreased and the accumulated dose do not increase any longer, c.f. figure 15.

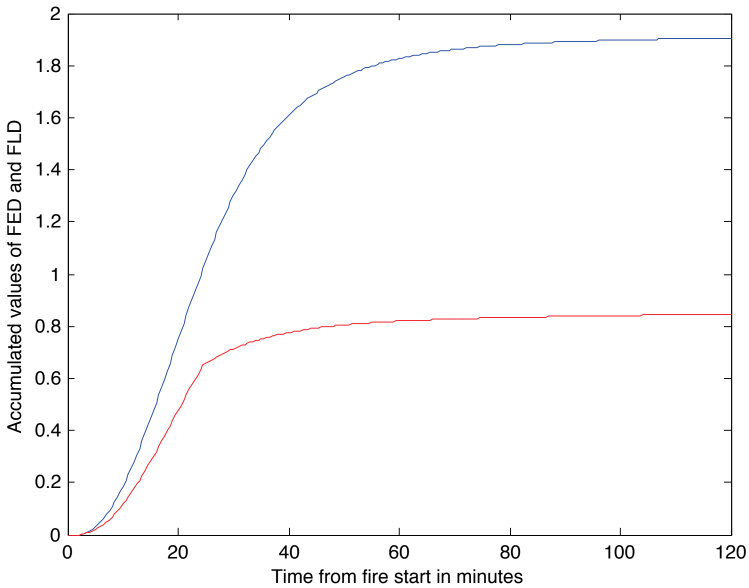


Figure 15. Fractional effective dose (blue line, top) and fractional lethal dose (red line, below) for persons evacuating from a tunnel with 5 x 5 m^2 cross section and air velocity of 0,5 m/s.

For scenarios with high air velocity and large cross section it might be assumed that the evacuation is performed without and problems. That is not necessarily the case. Even if the toxic dose is below the chosen criteria the evacuation could have to be performed in smoke, cf. figure 16 showing the evacuation situation for the 7 x 11 m^2 tunnel and 1 m/s air velocity.

It can be seen that the evacuation is performed almost completely in a smoke laden environment. This situation is similar in most cases and it can be concluded that the evacuation conditions are difficult in almost all situations in case of a fire in two ordinary cars.

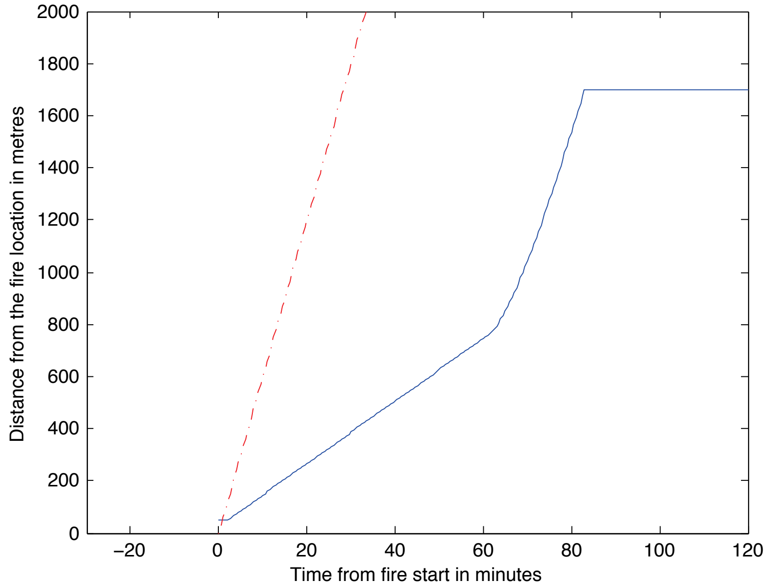


Figure 16. Location of persons (blue solid line) and smoke front (red hatched line) for evacuation in the 7 x 11 m^2 tunnel, 1 m/s air velocity and 2 minute recognition and response time (last condition in table 4).

6.8.3 Scenario 3. Articulated hauler fire

The fire development in the articulated hauler has an initial part where the fire grows rather rapidly followed by a second part where the growth rate is slower. But during the initial part the fire grows to 3 MW in 6 minutes which is close to an so called ultrafast fire growth. Therefore, the hauler fire must be considered as hazardous. Still, the recognition and response time is chosen to 5 minutes i.e. it is not controlled by the 3 MW criterion. The main results are found in table 5.

Table 5. Results for the articulated hauler fire scenario.

Cross section, m2	Air velocity, m/s	Rec&Resp time, min:sec	Dist to FED=0,3, m	Time to FED=0,3 or safe, min	Dist to FED=1, m	Time to FED=1, min	Time to FLD=1 or max FLD at 120 min, min or FLD
3x4	0,5	5:00	146	13	302	26,6	38,5
4x5	0,5	5:00	224	19,5	482	41,5	56,5
5x5	0,5	5:00	272	23,5	566	48	65,5
6x7	0,5	5:00	416	35,5	764	65	99
7x11	0,5	5:00	614	52	1088	92	0,75
3x4	0,5	4:00	158	13	320	26,5	39
6x7	0,5	4:00	434	36	782	65,5	99
7x11	0,5	4:00	626	52	1106	92	0,75
3x4	0,5	3:00	175	13,5	332	27	39,5
6x7	0,5	3:00	446	36	800	66	100
7x11	0,5	3:00	644	52,5	1124	93	0,75
3x4	0,5	2:00	194	14	356	27,5	40
6x7	0,5	2:00	>1700	22	>1700	-	0
7x11	0,5	2:00	>1700	22	>1700	-	0
3x4	1	5:00	248	21,5	470	40,5	54,5
6x7	1	5:00	560	47,5	1016	86	0,74
7x11	1	5:00	770	65	>1700	0,78	0,5
3x4	1	2:00	278	21	512	40,5	55

The consequences of this scenario are similar to the previous scenario. This has mainly to do with the rapid fire growth but also the fact that movement does not start until 5 minutes has passed, at least for the basic scenarios. Several calculations have been performed with shorter recognition and response times but it is still difficult to evacuate all the distance to the outside. Only for tunnels with large cross sections and a rapid recognition and response time the persons may reach the outside without being intoxicated. For those cases, looking at the person's locations as a function of time in relation to the location of the smoke front it can be seen that the persons move ahead of the smoke front. But this is only possible if the evacuation starts quickly, cf. figure 17. In other scenarios the situation is similar to the two-cars fire, see figure 16 for a typical resulting graph.

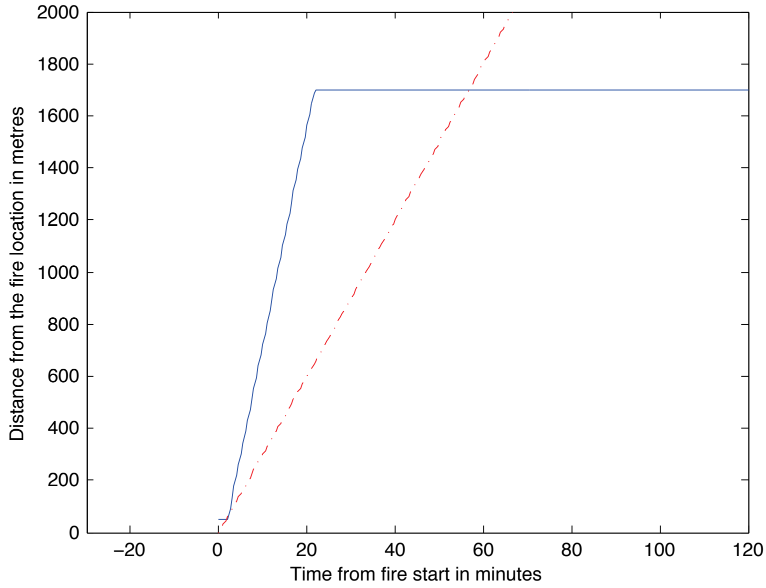


Figure 17. Location of persons (blue solid line) and smoke front (red hatched line) for evacuation in the 7 x 11 m^2 tunnel, 0,5 m/s air velocity and 2 minute recognition and response time.

The situation is improved as the air velocity can have a higher speed in the tunnel. This has been seen also for other scenarios.

It seems that if movement takes place in smoke the time delay to initiate movement, i.e. the recognition and response time, does not affect the over all results, figure 18.

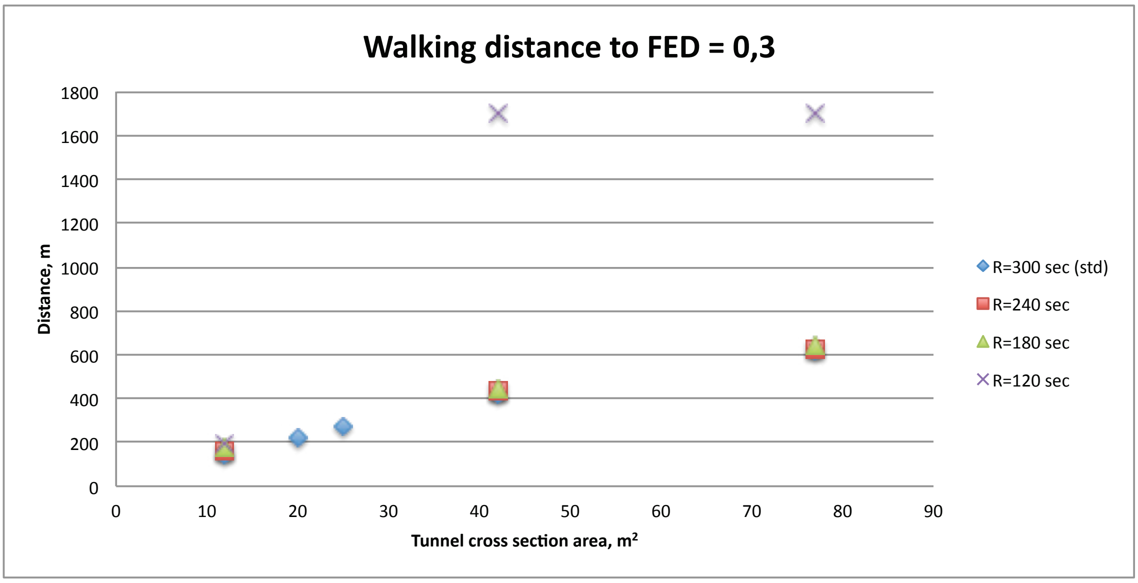


Figure 18. Distance the persons move until the FED value reaches 0,3.

The distances the persons can move until they have reached the so called design value in terms of FED value, FED = 0,3, are almost identical for each tunnel cross section and for a number of alternative delay times.

The reason for this may be that the conditions in the tunnel with respect to toxicity, visibility and so are not drastically different if the recognition and response times change a few minutes. The time it takes to move the distances to FED = 0,3 is almost one order of magnitude larger than the time scale for the recognition and response time. If, however, the delay time is small there is a chance that the persons can start their movement in a very early stage and can move in an unaffected tunnel, to reach the safe location outside the tunnel, figure 17.

6.8.4 Scenario 4. Bus fire

The bus fire is considered severe as the fire growth rate is close to the so called ultra fast fire development. This means that the conditions for evacuation become critical in an early stage even for tunnels with a large cross section area. The recognition and response time will also be short, i.e. 150 seconds which corresponds to the time for the fire to reach the 3 MW level. No calculations are done for the bus fire in the smallest tunnel because it is not likely that a bus will enter such a small tunnel. The results are presented in table 6.

Table 6. Results for the bus fire scenario.

Cross section, m2	Air velocity, m/s	Rec&Resp time, min:sec	Dist to FED=0,3, m	Time to FED=0,3 or safe, min	Dist to FED=1, m	Time to FED=1, min	Time to FLD=1 or max FLD at 120 min, min or FLD
3x4	0,5	150	-	-	-	-	-
4x5	0,5	150	128	9	146	10,5	10,5
5x5	0,5	150	134	9,5	158	12	12
6x7	0,5	150	164	12	206	15,5	17,5
7x11	0,5	150	>1700	22,5	>1700	-	0
7x11	0,5	180	194	15	296	24	0,9
7x11	0,5	240	176	14,5	278	23	0,9
6x7	0,5	120	>1700	22	>1700	-	0

It is significant that the sensitivity for a safe or unsafe situation is high in this scenario. Comparing the small shift in recognition and response time for the 7x11 m^2 tunnel from 150 seconds to 180 seconds indicates two totally different situations, figure 19. The same situation is valid for the smaller tunnel cross section 6x7 m^2 but then the evacuation has to start even earlier, cf. 120 seconds compared to 150 seconds. That is, however, not shown in figure 19.

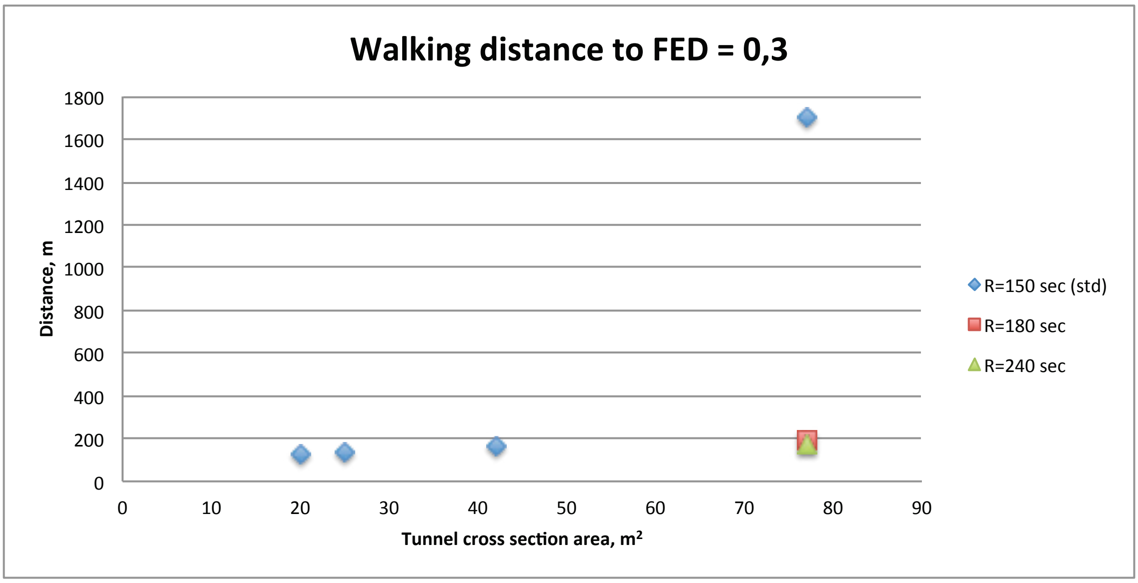


Figure 19. Walking distance to FED = 0,3 for a bus fire and with different recognition and response times.

If the persons start their evacuation rapidly they can evacuate the whole distance to the outside without being delayed by the presence of smoke. But if the recognition and response time is slightly longer the persons are hindered already after a quarter of an hour, cf. the results for the 7x11 m^2 tunnel and 120 s and 150 s delay. This is, of course, a result from the model calculations but indicate the importance to start the evacuation before being overwhelmed by the smoke. It shall be noted that the persons are assumed unexposed for the recognition and response time and for the first 50 metres. The smoke front is therefore only 10 metres ahead of the persons if they commence their evacuation after 120 seconds as the smoke travels with 0,5 m/s.

The situation with a bus fire is severe also considering that the fire is located in the means of transportation from the fire, if evacuation is supposed to be performed using the bus. The persons, in this scenario, have to evacuate by foot and the conditions of the passengers are therefore important in estimating the outcome of the bus fire accident.

6.9 Concluding remarks using the one-dimensional model

Comparing the results from the different fire scenarios some patterns can be seen.

The most obvious is that depending on when the evacuation starts the persons may either be trapped in the smoke and can then move a certain distance or on the other hand the persons can move ahead of the smoke zone to reach a safe location. If, in the latter case, movement occurs in the smoke free environment it can be performed rather safely as the smoke front moves much slower than the normal walking speed. The time to reach the tunnel entrance is independent on the tunnel shape as only distance and movement velocity determines the time to reach safety.

But if movement occurs in smoke the fire development is one key factor that determines the duration the persons can stay in the tunnel without getting unconscious. Figure 20 shows how long the persons can walk before they accumulated the toxic dose equivalent to a FED value of 0,3.

The figure shows the distances for the situations where the basic values on recognition and response time were used. Surprisingly, the relationship between distance and tunnel cross section area is linear. This was not assumed before doing the calculations, as the equations used in the algorithm in the model are far from linear.

This relationship is of course only valid for the movement in smoke and if the persons can move away from the smoke. For one or more cross section areas there is a discontinuity in the curve, cf.

the bus fire relation, and then the linearity does not exist. However, at the moment extrapolating from these results is not recommended.

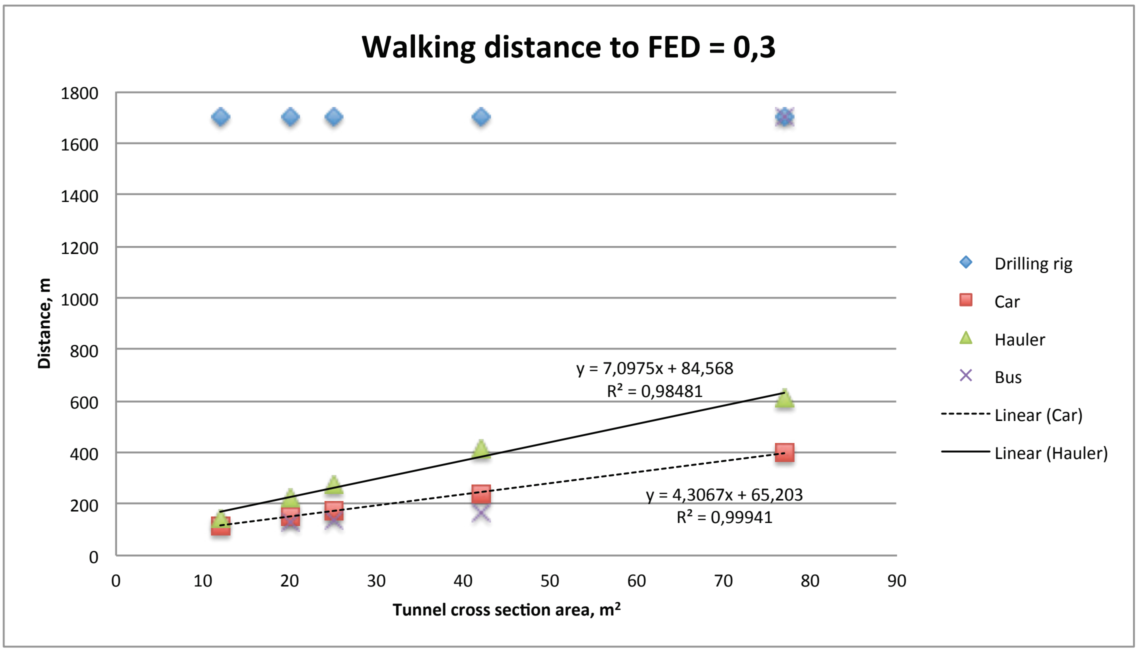


Figure 20. Walking distance to FED = 0,3 for all fires and with different tunnel cross section area.

It was also, beforehand, assumed that the air velocity in the tunnel would have an effect on the possibility to evacuate safely, or at least continue for a longer period of time. This showed to be true as can be seen in figure 21, showing the location where FED = 0,3 is reached for different fire scenarios and for two air velocity values, i.e. 0,5 m/s and 1,0 m/s.

It must also be mentioned that there may be an effect on the fire development for an increased air velocity but that is not taken into account in the calculations.

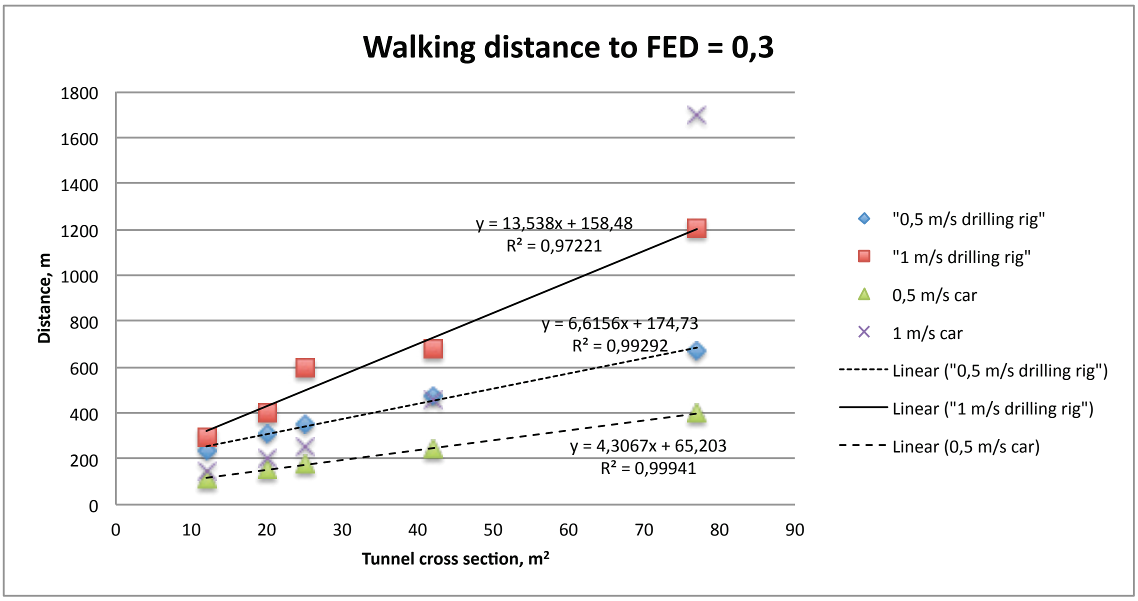


Figure 21. Walking distance to FED = 0,3 for two fires and with different tunnel cross section area and for two different air velocities.

Most of the comments above has been related to the critical evacuation condition FED = 0,3 but according to the model and it's assumption movement continues until the FED value has reached 1,0. Comparing the distance a person can move to reach the two levels of criticality there is almost a factor of two in difference, figure 22.

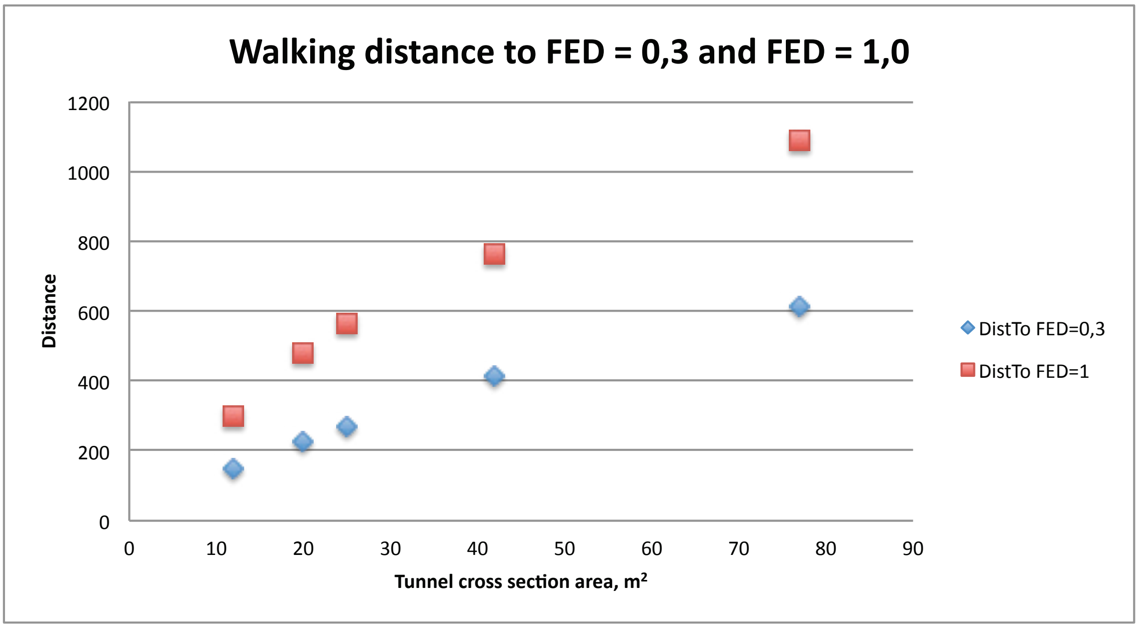


Figure 22. Walking distance to FED = 0,3 and to FED = 1,0 for the articulated hauler fire using the basic scenario conditions.

This difference in distance between FED = 0,3 and FED = 1,0 can therefore be seen as a safety factor in designing the longest distance to a safe location for the persons in a tunnel.

Part from analysing the maximum distance the persons working in a tunnel can move before reaching the untenable conditions other aspects of the fire hazard may be relevant to analyse. In many cases the heat radiation from the flames determine whether or not the fire poses a threat to the persons. This has also to do with determining the possibilities the persons have to fight the fire.

The heat radiation from the fire flames can be determined for the fire scenarios and as a function of time. However, the calculations are rather time consuming and a simplified approach can be used. Assuming the fire starts in two passenger cars it can be determined if the fire successfully can be extinguished within the time frame when the persons have to start evacuating. In the assumptions in section 6.6 it was stated that the persons might try to extinguish the fire as long as it is smaller that 3 MW in HRR.

If it is assumed that the fire can be treated as a point source and 30% of the total heat output is radiated from the fire a distance of 5 m is the closest distance a person can be in order to avoid pain on naked skin. A tolerable heat flux of 2,5 kW/m^2 is used as the radiation criteria which is a level likely to create pain but not skin damage, Purser (2008).

At this distance the fire is highly unlikely to be affected by the extinction attempts. On the other hand, shielding the face by a glove protected hand can make it possible to get closer to the fire. But the calculation can also be used to get an idea of the possibility for the persons to walk pass the fire if it continues to grow and depending on the size of the tunnel. A fire of this size in a small tunnel may result in conditions impossible to walk pass due to heat radiation. In a large road tunnel the same fire poses a smaller threat. The heat flux can be calculated using the following expression:

Closest distance = $\sqrt{\dfrac{0,3\cdot\dot{Q}_{tot}}{4\pi\cdot 2,5}}$ [m]

The HRR $\dot{Q}_{tot}$ should be expressed in kW.

6.10 Additional smoke movement calculations

One of the objectives for the evacuation analysis was to investigate how the situation developed if the fire was located elsewhere than in the most remote part of the tunnel. This situation was not possible to investigate using the earlier described Matlab model. The reason for this is that the model assumes that the smoke can only move in one direction, i.e. towards the tunnel entrance.

If a fire occurs in the middle of a tunnel having only one entrance the air velocity prior to the fire is directed towards the entrance. In the initial phase of the fire the Matlab model can be used as the smoke will follow the current air flow. But, it is assumed that the fire will affect the ventilation tube beneath the tunnel ceiling and air from the tube will enter the tunnel just above the fire in the centre part of the tunnel. The air flow pattern will now be disturbed and a different situation will occur on how the smoke will be distributed.

The questions are if the smoke will turn immediately above the fire and follow the air stream out to the tunnel entrance or will a part of the smoke move along the tunnel ceiling, finally reaching the remote part of the tunnel? If the smoke follows the ceiling how much will move into the tunnel and how much will follow the air flow created by the air supply above the fire, i.e. move directly towards the tunnel entrance?

In order to investigate how the smoke movement will change due to the broken ventilation tube a smoke movement analysis was performed using the software Fire Dynamic Simulator (FDS), described in (McGrattan, Hostikka, Floyd, Baum, Rehm, Mell & McDermott, 2008). For the analysis, version 5.2 was used in the simulations. The simulations were made in isolation from the evacuation analysis so there is no possibility to determine the evacuation distances and other resulting parameters as with the Matlab model. But the simulation results give an idea about what may happens with the smoke movement and how that in turn may affect the evacuation, however, from a qualitative perspective.

6.10.1 Conditions

The tunnel for the FDS simulations is only 400 m and has a cross section of 5 x 5 m^2. At 200 m from the entrance it assumed that a fire occurs (between x=200 m and x=201,6 m) and it grows linearly from 0 kW to 4800 kW in 30 seconds. The fire has a horizontal area of 3,2 m^2 and is located 0,4 m above the ground level. Before the fire is assumed to start developing the calculations have been performed long enough to create an initial air stream in the tunnel, i.e. the 0,5 m/s air velocity.

In the most remote part of the tunnel an air supply is located beneath the ceiling providing the tunnel with fresh air and is designed to give an initial air velocity at 0,5 m/s across the tunnel cross section.

This air supply is turned off as the fire destroys the ventilation tube above the fire. The air will then enter the tunnel above the fire, slightly towards the tunnel entrance, to take into account that the fresh air exits the ventilation tube at a location where the tube is undamaged by the fire and not right above the fire. Initial simulations showed that the exact location of the secondary air flow exit was important and it was therefore assumed that the air tube was unaffected approximately 3 m away from the fire in the direction to the tunnel entrance (x=205 m).

When the fire destroys the ventilation tube the air flow in the remote part is reduced. Instead, the air flow above the fire is turned on, ending with the same air flow as before the fire starts. Figure 23 shows the geometry of the tunnel and the location of the fire and the two locations where air is entering the tunnel, before and after the fire has started. Also, an obstacle was present in the most remote part of the tunnel simulating a drilling vehicle. Both the air supply and the obstacle were located approximately 20 m from the end of the tunnel, i.e. 380 m from the entrance.

The simulations presented below uses a grid with cubical elements with side length of 0,2 m. The tunnel is then constructed using approximately 1,1 million cells. The computations are done by dividing the tunnel in seven sections performing a parallel computation of all sections simultaneously. A sensitivity analysis using a grid with cube elements having a side of 0,1 m was done for a part of the calculation and the difference between the two was considered small.

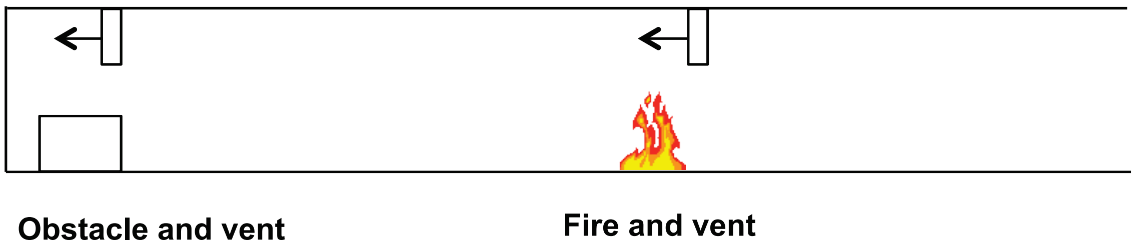


Figure 23. Schematic description of the tunnel used for the smoke movement simulations.

6.10.2 Results

The simulation was first run in 10 minutes without any fire present to create the initial air flow in the tunnel. At 10 minutes the fire started and the air flow was changed from the tunnel end to the location slightly above the fire. The simulation continued for another 20 minutes.

The assumptions regarding the smoke movement when the fire destroyed the ventilation tube was confirmed and part of the smoke continued to move towards the remote part of the tunnel. Figures 24-27 show the smoke distribution at different time steps. The three vertical lines in the figures left of the fire indicate the mesh boundaries and are located at (from left) 50 m, 100 m and 150 m from the most remote part of the tunnel. The fire in the right part of the pictures are located at 200 m from the work place and the tunnel continue another 200 m to the right but this is not visible in the figures.

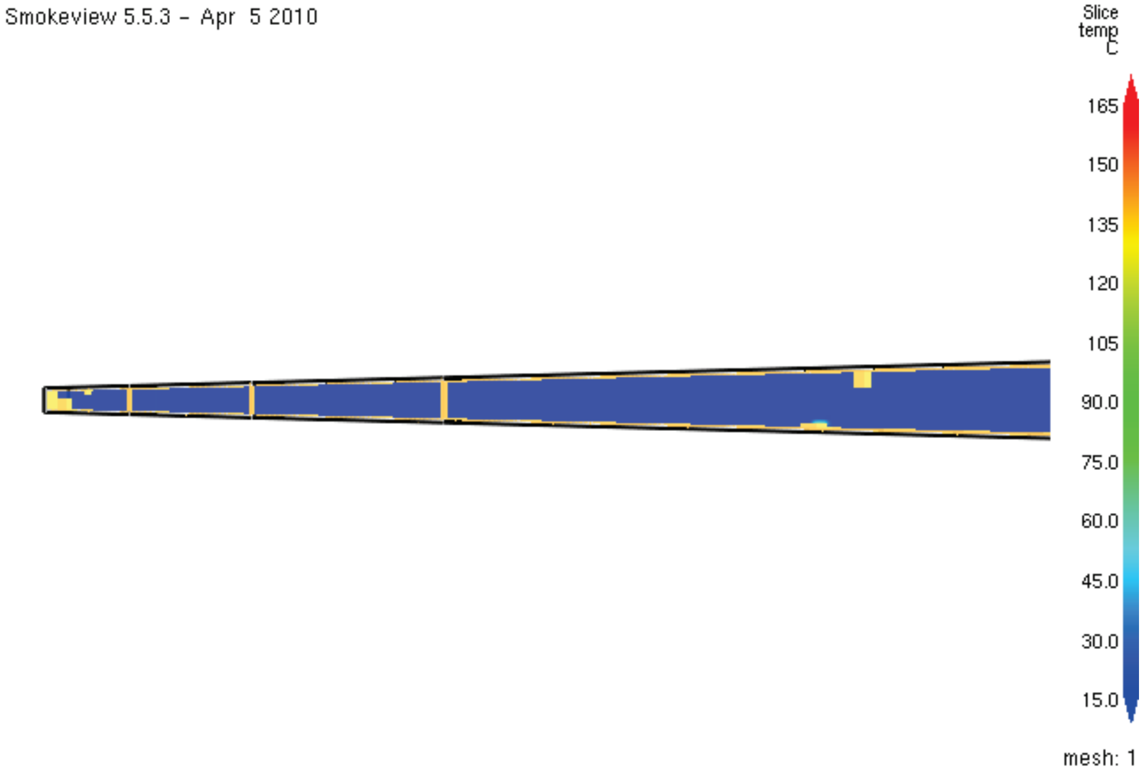


Figure 24. Smoke distribution at 1 second from the start of the fire. Vertical lines are at 50, 100 and 150 m from left to right. The fire is located at 200 m from the end of the tunnel.

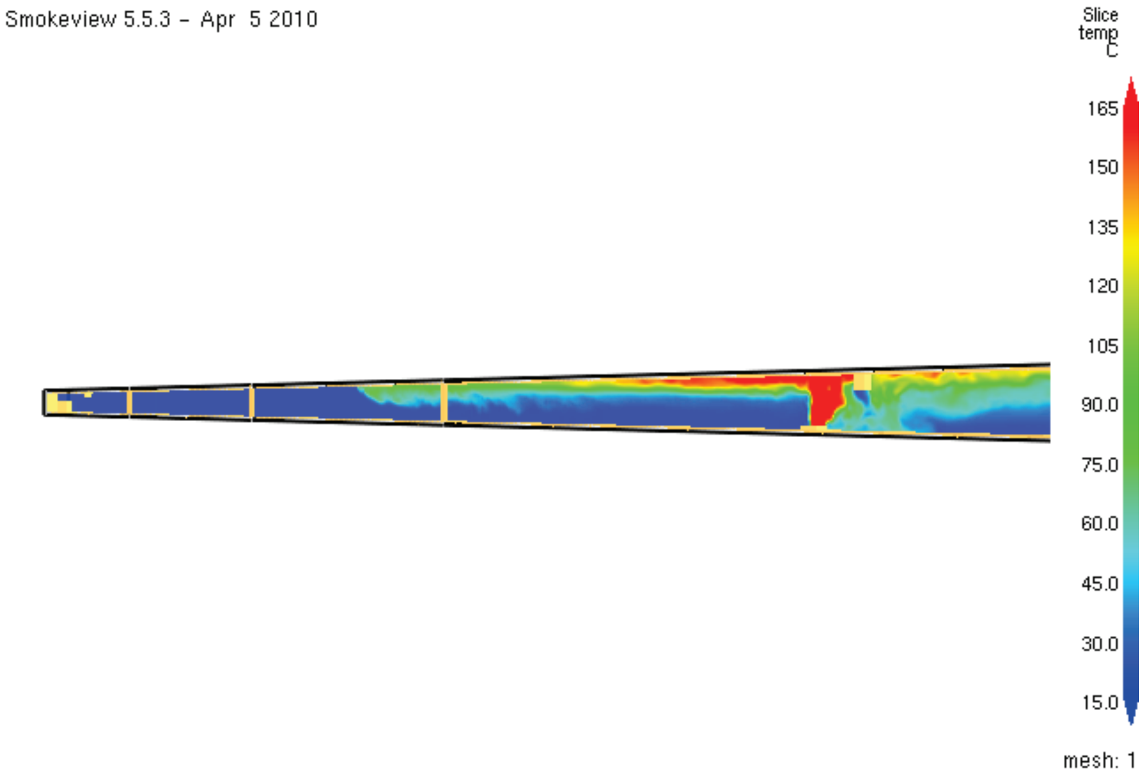


Figure 25. Smoke distribution at 1 minute the start of the fire. Vertical lines are at 50, 100 and 150 m from left to right. The fire is located at 200 m from the end of the tunnel.

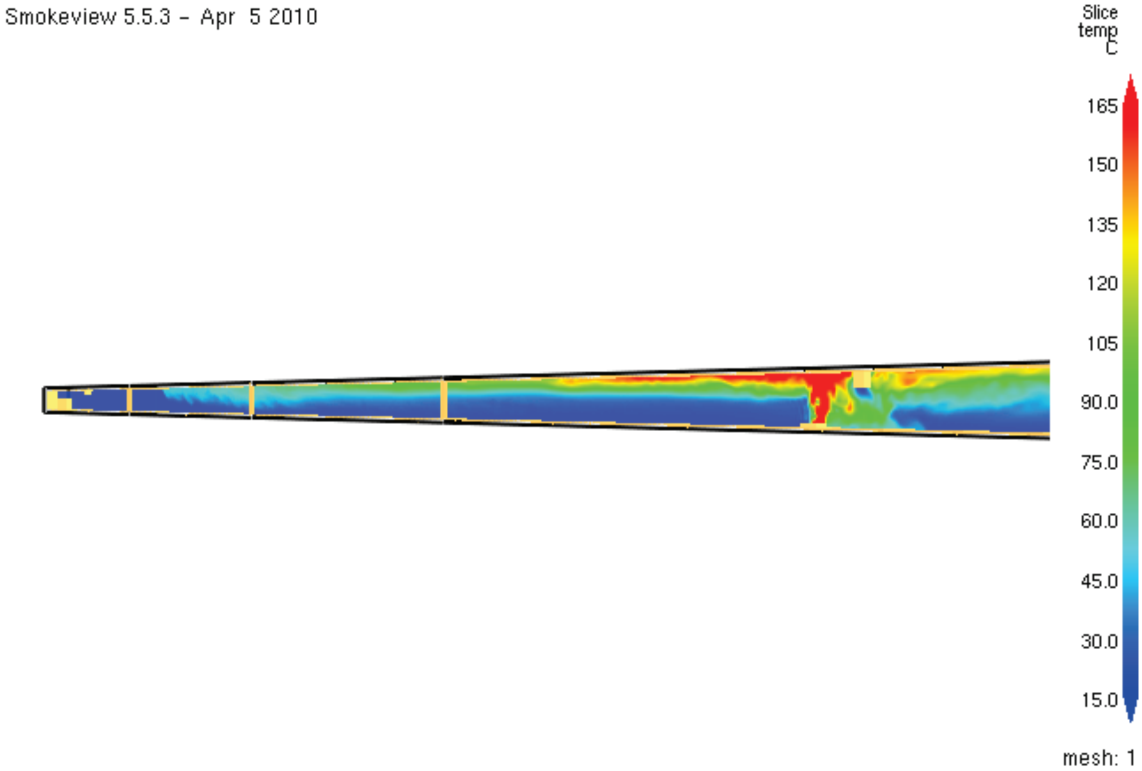


Figure 26. Smoke distribution at 2 minutes from the start of the fire. Vertical lines are at 50, 100 and 150 m from left to right. The fire is located at 200 m from the end of the tunnel.

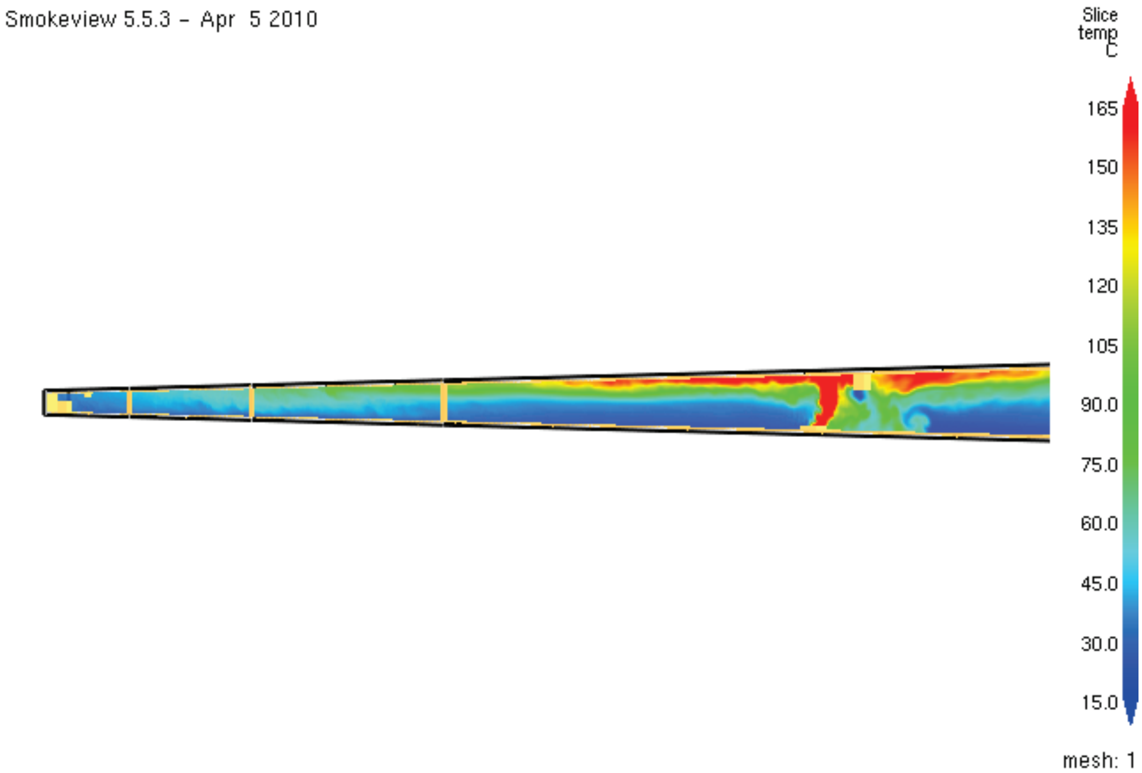


Figure 27. Smoke distribution at 5 minutes from the start of the fire. Vertical lines are at 50, 100 and 150 m from left to right. The fire is located at 200 m from the end of the tunnel.

Most of the smoke will, however, move along with the draught created by the air at the new location of the air supply. As part of the smoke, though, eventually will reach the most remote part of the tunnel the persons staying there, tunnel workers, have to have a safe place to move to and they also have to be notified that a fire has occurred. In the calculation presented above the smoke reached the most remote location of the tunnel approximately 3 minutes after the fire stared. When the smoke hits the tunnel end it bounces back and moves along the floor, i.e. below the hotter smoke coming directly from the fire. The tunnel cross section is then effectively covered with smoke.

In a real tunnel the shape of the tunnel is not as straight as in the calculations and it will most likely not be possible to observe the fire from a place of work in a tunnel. It is, therefore, not possible to stay in the tunnel and wait until it has been extinguished. Smoke will reach even remotely located places but it takes some time.

In order to prevent the persons staying in the most remote part of the tunnel from being trapped at their location without any option of rescue they must be informed about the fire as soon as possible. The need for a fire alarm is vital to be able to notify the persons in the tunnel so they can prepare to protect themselves. At the location 200 m from the fire in the tunnel above the temperature is not that high but the smoke may well be very toxic considering the exposure time and breathing equipment is necessary for survival.

The scenario assumes that the fire destroys the air tube beneath the tunnel ceiling. Flames from the fire must, therefore, reach the air tube and the likelihood that this happens depends on the size of the fire and the tunnel height. Using simple engineering equations an approximation of the flame height can be calculated, Heskestad (2008). Such a calculation is made for the two cars fire assuming that the fire can be approximated by a pool fire with a heat release rate of 3 MW/m^2, which is equivalent to a fire in petrol or heptane. Using this HRR per area assumption on the two cars fire results in a flame height curve presented in figure 28. The figure clearly shows that a fire of that size can create a harmful situation for the supply air tube, especially if the tunnel height is less than approximately 5 m. One should also bear in mind that the sample calculation deviate from a car fire which is also characterised by the flames from the car windows leading to several smaller flames compared to the single sample flame.

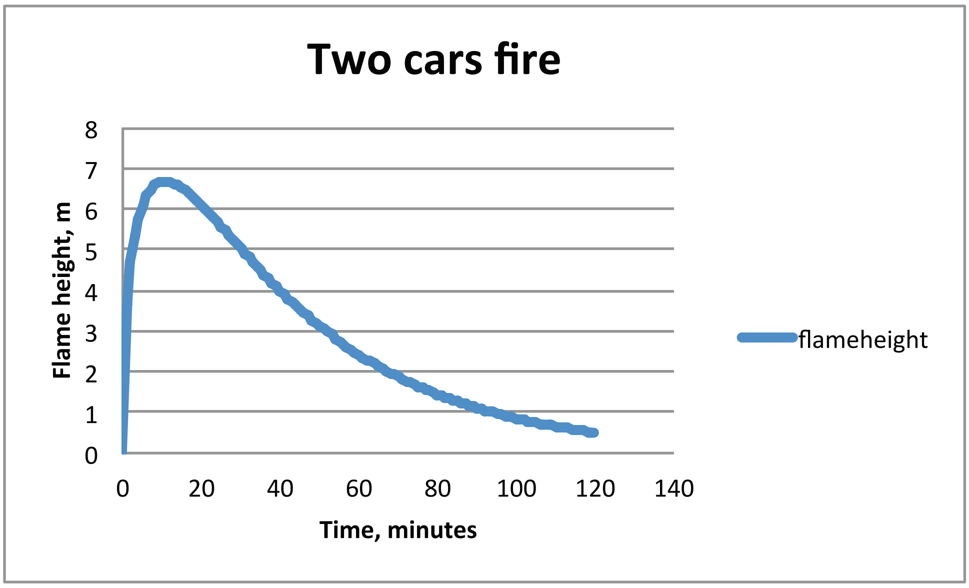


Figure 28. Approximation of flame height from fire in two passenger cars.

7 Discussion

7.1 Results from the analysis

Naturally, the results from an analysis depend on the initial conditions for the analysis. However, some general trends can be concluded from the model calculations presented in the previous chapter. As the conditions for evacuation becomes worse for larger fires and smaller cross sections it is natural to perform a safety strategy based on the current conditions which are relevant for the tunnel to be constructed. This can lead to a decision about the relevant fire characteristics that shall form the basis for the analysis.

If, for example, a small wastewater tunnel is to be constructed there may be no reason to design the safety strategy on the assumption that the fire will be located in a visitor's bus. Instead a smaller fire size may be a more appropriate choice. The choice should, though, be made to include a large proportion of fires relevant for this situation, i.e. to handle the uncertainty in fire characteristics by making a choice on the "safe side". This is what engineers call a deterministic or scenario-based approach. The design can also be made by using a probabilistic approach by explicitly consider both fire frequency and fire consequences but for the construction phase this may be an inappropriate method considering the efforts that has to be invested in the analysis.

One of the main questions managing safety issues is related to the operation of the fan supplying the construction site with fresh air and whether or not it shall be switched off in the case of a fire. This is an example of questions that can be included in a safety analysis for the current tunnel construction. It is not possible to provide a simple yes or no to this question as the outcome may be different depending on where the fire is located, where the persons are located, where the nearest escape route or refuge chamber is located and many other aspects.

But to provide some guidance on how to treat the problem, the three fundamental evacuation scenarios presented in chapter 5 can be studied. In each fundamental evacuation scenario two locations where the persons may be present are identified. This gives six cases differing in the locations of the fire, the persons and the safe position (escape route or refuge chamber). By analysing the evacuation conditions for these six cases a general picture of the ventilation strategy can be obtained.

In table 7 a description is provided for the conditions for these cases and depending on whether or not the air supply system is in operation or is shut down. The example assumes that the fire can be characterised by the second fire scenario, i.e. fire in the two passenger cars. The discussion also assumes that there will be only one fire at a time.

Table 7. Analysis of fundamental evacuation scenarios.

Location	Description of the conditions and necessary assumptions
A1	If the air supply system is running the persons can evacuate to the nearest escape route and the distance should be according to the information in figure 20. The persons may attempt to fight the fire but can evacuate in smoke if necessary. If the fan is shut down the conditions near the fire becomes worse as concentrations of toxic components are higher and the visibility is poorer. If the persons can initiate their evacuation and move away from the smoke zone they may evacuate safely to the outside.
A2	If the fan is running the persons must be notified about the fire between 4-8 minutes from the fire start, depending on the cross section area, if they are to start moving to the outside before the smoke zone arrives to the location of the most remote escape route or refuge chamber. If the persons are located closer to the tunnel entrance the delay time can be longer and they can still evacuate safety.

	If the fan is shut down the persons can most likely evacuate rather safely if they are notified about the fire by a fire alarm.
B1	As long as the fan is running the environment for the persons can be assumed good. They must, however, be notified of the fire very early in order to reach the escape route or the refuge chamber. The problem for them is the possibility that the tube providing supply air may be destroyed by the fire and according to the calculations in section 6.10 the smoke will them move towards them with a high speed. The smoke velocity will depend on the conditions but for the example calculation it was approximately 1 m/s. The time when the tube is destroyed depends on the fire development and the tunnel height and it can be determined by a flame height calculation. If the fan is shut down the situation is better as the persons do not risk facing the smoke coming against them. They can most likely move towards the escape route or refuge chamber without meeting the smoke as the smoke previously was directed towards the tunnel entrance and will not turn back immediately. Smoke will eventually spread also into the tunnel so a fast notification is needed.
B2	This situation is similar to the conditions relevant for location A1. No further analysis is needed as long as the persons are close to the fire and can act in the same manner as the persons at location A1. It is assumed that the persons evacuate towards the tunnel entrance even if it is closer to an escape route or refuge chamber further into the tunnel. The situation can become worse if the person move into the tunnel reaching for a safe location and the situation can develop as for location B1 but with the smoke coming from behind when the air tube is destroyed.
C1	If the fan is running and the air tube is intact the situation will be similar to the conditions for location A1. The persons can evacuate towards the tunnel entrance is a rather smoke free environment and can perhaps reach the escape route or refuge chamber. Whether or not they will reach this safe location depends on the fire development in conjunction with the tunnel size. The fire escalates and will at a certain time result in heat radiation levels which prohibits a safe passage of the fire. For example at 3 MW fire will produce a radiation level of 2,5 kW/m^2 at 5 m distance from the fire that is the maximum allowed heat flux a person can withstand (naked skin). The persons must then be notified very early in order to reach the downstream side of the fire. Unfortunately, they will then enter the smoke filled zone. But stratification of the hot smoke close to the fire may provide a opportunity to advance further to the escape route or the refuge chamber. This conclusion assumes that the air tube is not destroyed by the fire. If that happens before the persons have reached the location of the fire they are faced with the smoke coming against them. A fast detection of the fire and a fast notification of the persons is necessary in order to provide a safe evacuation. If the fan is shut down the possibility to pass the location of the fire is even worse as the smoke is not transported away from the location by the air supply providing an air draught in the tunnel. An early notification is then the only possibility for a successful evacuation.
C2	This situation is similar to the one for location A2. The persons will most likely detect the smoke or can be notified by the fire alarm in an early stage of the fire before the smoke has reached the location. Evacuation can be performed ahead of the smoke zone. The conditions will not depend on whether or not the fan is running or is shut down. The margin of safety is increased if the fan is shut down but also for the case

	when the fan is running evacuation can be performed. Destruction of the air tube will not affect the persons at this location.

As can be seen in the table above there are both situations gaining on the running fan and those where it is better to turn off the fan. As there is no obvious solution to this problem an analysis has to be performed to evaluate the best decision out of a number of poor alternatives. In table 8 a recommended decision and a short summary of the six alternative locations are described in terms of what to do with the fan.

Table 8. Air supply fan decision analysis in case of a fire.

Location	Recommended decision and the reason for the choice.
A1	Keep the fan running. The evacuation can be performed in smoke. If the persons decide to leave the place of work they can evacuate in a better situation and move ahead of the smoke zone. If the fan is turned off they can still move away from the smoke zone but only if they leave early in the fire development.
A2	Turn off the fan. The smoke zone will stay at the location of the fire and the persons can evacuate safely.
B1	Turn off the fan. The persons can move towards the escape route or refuge chamber without facing the smoke coming from the air tube being destroyed by the fire. The persons need an early notification.
B2	Keep the fan running. The situation is similar to A1. The evacuation can be performed in smoke. If the persons decide to leave the current location they can evacuate in a better situation and move ahead of the smoke zone. If the fan is turned off they can still move away from the smoke zone but only if they leave early in the fire development.
C1	Turn off the fan. The persons can move towards the escape route or refuge chamber without facing the smoke coming from the air tube being destroyed by the fire. The condition near the fire is severe but there is a chance the persons can walk past the fire if they are notified early.
C2	Turn off the fan. The smoke zone will stay at the location of the fire and the persons can evacuate safely.

The best recommendation in this analysis seems to be to turn the air supply fan off in the case there is a fire. The reason for this recommendation is that for some situations the persons evacuating can meet the fire smoke coming against them when the fire destroys the air tube. The situation will then change dramatically and make the conditions for evacuation worse. If the fan is turned off immediately as the fire is detected the whole air movement system is slowed down and the persons will not face any rapid changes in the situation. However, for the situation the fire is located between the persons and the safe location, i.e. location C1, the situation is very severe both if the fan is running and if it is turned off. When the fan is running they risk to face the smoke coming from the draught created by the destroyed air tube. If the fan is turned off they will move towards the fire area where the conditions are severe and perhaps not possible to pass the fire.

The situation can be improved if the fan is running a while after the fire is detected but not that long that the fire grow and can destroy the air tube. Looking at the sample calculation in section 6.10.2 the time to destroy the air tube is short. A more refined analysis can be performed to determine the time span the fan can continue to run to provide as good conditions as possible for the persons evacuating the tunnel under construction.

One aspect that has resulted from the analysis of evacuation safety is the need for a rapid response by the persons located in the tunnel. This rapid response needs a fast fire detection system and a way to communicate the occurrence of a fire to all the relevant persons. If the persons are notified that a fire has occurred they can initiate their evacuation to a safe location.

If it is possible the evacuation can use vehicles present in the tunnel. To save time during the evacuation most vehicles could initially be parked so they do not first have to be turned, i.e they should have their front pointing towards the tunnel exit.

Other aspects providing an evacuation-friendly environment are the use of emergency lightings and escape route markings. A power failure can result from a fire and an emergency lighting can then assist the persons during the evacuation.

To check that the evacuation strategy works and for education purposes evacuation drills must be performed regularly. Depending on the purpose of the activity; education or test the design of the drill must be considered. An education activity must be part of a systematic safety management program.

7.2 Methodological assumptions

Initially the part handling evacuation issues for tunnel construction sites started with a literature survey to establish an overview of the area. Unfortunately, not much was published about evacuation conditions during fires in underground construction sites. Some incident reports mentioned that the workers hade to evacuate in difficult situations but no quantitative information was provided.

Therefore, the evacuation analysis had to rely on construction site visits, participation in evacuation drills and the development of an engineering tool which could be used determine the evacuation conditions for a specified fire scenario. The visits were mainly conducted to get an overarching perspective of the different conditions relevant for tunnel construction sites. This qualitative information was used later in the model development in a quantitative manner. During the visits more quantitative data could have been collected but mostly this was not possible as the visits were performed during the normal excavation or drilling operations of the tunnels. More quantitative data, therefore, had to be collected during simulated fire evacuations. One such was performed in the Tunnel Boring Machine in Hallandsås and data was collected on physical parameters like walking speed and psychological parameters like attitude towards safety issues. This information was also used in the development of the model.

Still, trying to establish the outcome of an evacuation using a model tool will be a simplification of the reality and a number of assumptions have to be made. All these will of course affect the outcome of the modelling results. The results must not be seen as the truth but rather as examples of a possible outcome and an input for decision making about how to manage the evacuation safety issues at a tunnel construction site.

The main objection concerning the results is based on the assumption of a one-dimensional smoke spread in the tunnel. As the smoke is warmer than the air temperature in the tunnel there will be a smoke stratification leading to a smoke accumulation below the ceiling and a relatively clear zone below the smoke. In the model it is assumed that the conditions are homogenous across the tunnel cross section. This is a true situation a distance away from the fire when the smoke have had an opportunity to mix with the air but close to the fire this will give a wrong result. However, it is assumed that during the initial part of the evacuation no toxic exposure occurs, partly to consider the issue with stratification. But most likely the model assumes a higher exposure of toxic gases during the first part of the evacuation, though providing conservative a result.

What is lacking in the development of the evacuation model is a complete validation process. This has not been performed, as it is almost impossible to do. Instead, the different sub-models in the combined evacuation and smoke spread model have been validated separately. The smoke spread part of the model has to some extent been validated by a comparison with full-scale experiments (Ingason, 2005) and the evacuation part of the model is based on well-established expressions on for example toxic accumulation in the body (Purser, 2008) and the relationship between walking velocity and visibility (Jin, 1985). It can, therefore, be assumed that the predictions made by the model have a fair accuracy given the limitations in the model.

In a project like this, one would perhaps also have simple answers to many of the questions related to evacuation problems in tunnel construction sites. This could be for example how close must escape routes be located, is there a need for escape route lightings, is there a benefit from using short term air masks and how should the fresh air supply system be operated in the case of a fire. Unfortunately, not many of those questions can be answered as it depends on the current conditions and what safety design criteria are chosen. The report provides a framework for how to deal with evacuation issues and how to perform such an analysis. Some guidance is provided based on general assumptions about for example a determined fire characteristic. An example is the discussion about how to operate the fresh air supply fans in the case of a fire.

8 Conclusions

The work presented in this report has come to the following conclusions.

The safety to persons in a tunnel being constructed depends on both the physical conditions present and the implementation of a proper safety management system. The latter is especially important for a construction situation involving several contractors or subcontractors, as the share of responsibility has to be clarified.

The evacuation safety of the persons working in a tunnel or visitors in the case of a fire depends on the fire development, the tunnel cross section and aspects related to evacuation. This means that an analysis of distance to the nearest safe location must consider these factors.

The analysis clearly shows that the shortest distance to an escape route or a refuge chamber is dependant of the tunnel cross section for the same assumed fire development. A tunnel with a small cross section need to have shorter distance between the escape routes.

If an evacuation has to be performed in a smoke contaminated environment the evacuation is severe almost independent on the fire characteristics.

Mechanical ventilation providing fresh air to the tunnel work places shall in most cases rather be switched off than continue to run. The fan may be operated as long as the risk to destroy the air supply tubes is low.

A high fresh air velocity is better in terms of evacuation safety. However, a higher velocity of the air current in the tunnel also affects the HRR development and this combined effect has not been investigated in the project.

In order to provide a safe evacuation in the case of a fire a fire alarm system shall be provided in the tunnel construction site. The alarm system must be designed to provide fast and clear information to the relevant persons. This is most important for situations where the fire may block the way to the nearest escape route, which turned out to be the most complicated situation for evacuation.

It is assumed that education of the persons working in the tunnel and performing evacuation exercises lead to shorter delay times in the case of a fire. There is evidence of this assumption from one evacuation drill but a further investigation has to verify this.

In most cases analysed in this report a fire in a passenger bus is very severe in terms of evacuation and special attention should be taken when visitors are allowed to enter a tunnel during the construction phase.

Finally, the analysis show that the design of the safety concept for the workers in a tunnel cannot rely only on so called rules of thumb. A serious analysis should be recommended in order to provide for a safe evacuation in the case of a fire in a tunnel under construction.

9 References

AFS 2010:1 (2010) Berg- och gruvarbete. Stockholm: Arbetsmiljöverket.

Bergqvist, Frantzich, Hasselrot & Ingason (2001)

Ingason, Bergqvist, Lönnermark, Frantzich & Hasselrot (2005)

Canter, D., Breaux, J., Sime, J. (1980). Domestic, Multiple Occupancy, and Hospital Fires. In Fires and Human Behaviour 1st ed., Ed. Canter, D. John Wiley & Sons.

Frantzich, H. (2000). Utrymning av tunnelbanetåg. Experimentell utvärdering av möjligheten att utrymma i spårtunnel. Rapport P21-339/00. Karlstad: Räddningsverket.

Frantzich, H. (2001). Occupant Behaviour and Response Time – Results from Evacuation Experiments. Proceedings of the 2nd International Symposium on Human Behaviour in Fire, pp 159-165.

Frantzich, H., Nilsson D. (2003). Utrymning genom tät rök: beteende och förflyttning. Report 3126, Lund: Dept. of fire safety eng. Lund University.

Frantzich, H., Nilsson, D., Kecklund, L., Anderzén, I. & Petterson, S. (2007). Utrymningsförsök i Götatunneln. Report 3140, Lund: Department of Fire Safety Engineering, Lund University.

Frantzich, H. & Nilsson, D. (2009). Evacuation in complex environments - An analysis of evacuation conditions in a nuclear power plant and a tunnel construction site. Proc. of the 4th International Symposium on Human Behaviour in Fire, Cambridge 13-15 July 2009.

Fridolf, K., Nilsson, D. & Frantzich, H. (2011). Fire evacuation in underground transportation systems – A review of accidents and empirical research. Accepted for publication in Fire Technology.

Heskestad, G. (2008). Fire plumes, flame height, and air entrainment. In The SFPE Handbook of Fire Protection Engineering, 4th ed. pp 2-1 - 2-20. Ed P DiNenno. Quincy: National Fire Protection Association.

Ingason, H. (2005). Fire dynamics in tunnels. In Beard, A., & Carvel, R. (Eds.) The handbook of tunnel fire safety. London: Thomas Telford Ltd.

Ingason, H., Lönnermark, A., Frantzich, H. & Kumm, M. (2010). Fire incidents during construction work of tunnels. SP Report 2010:83, Borås: SP Technical Research Institute of Sweden.

Jin, T., Yamada, T. (1985). Irritating effects of fire smoke on visibility. Fire Science and Technology, Vol. 5, No. 1, pp. 79-90.

Kumm, M., Andreasson, R. (2009). Insatsövning Hallandsåstunneln 081107 Emergency Exercise Hallandsås tunnel 7th of November 2008. Västerås: Mälardalens högskola.

Kumm, M. (2010). Rescue operations during construction of tunnels -a study of the fire and rescue services possibilities and their interaction with the tunnel contractor. Report SiST 2010:11. Västerås: Mälardalens högskola.

McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., Mell, W. & McDermott, R. (2008). Fire Dynamics Simulator (version 5) Technical Reference Guide. Volume 1: Mathematical Model. NIST Special Publication 1018-5. Gaithersburg: National Institute of Standards and Technology.

Moss Haber, G. (1980). Human behaviour in fire in total institutions; A case study. In D. Canter (Ed.), Fires and Human Behaviour (pp. 137-154). Chichester: John Whiley & Sons, Ltd.

Nilsson, D. & Frantzich, H. (2007) Vägval vid utrymning - utrymningsförsök med gröna blinkande lampor vid nödutgångar. Report 3141, Department of Fire Safety Engineering, Lund University, Lund.

Proulx, G., Sime J.D. (1991). To prevent 'panic' in an underground emergency: why not tell people the truth? Proc. of the Third International Symposium on Fire Safety Science. London: Elsevier, pp 843-852.

Purser, D. A. (2008). Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In The SFPE Handbook of Fire Protection Engineering, 4th ed. pp 2-96 - 2-193. Ed P DiNenno. Quincy: National Fire Protection Association.

Shields, T. J., & Boyce, K. E. (2000). A study of evacuation from large retail stores. Fire Safety Journal, 35(1), 25-49.

Sime, J. D. (1984). Escape behaviour in fires: 'Panic' or affiliation? PhD thesis, University of Surrey, Guilford.

Sime, J. D. (1985). Movement toward the familiar, person and place affiliation in a fire entrapment setting. Environment and Behaviour, Vol. 17, No. 6, pp. 697-724.

Appendix A, How to perform an evacuation exercise.

In most countries authorities require that a construction site work systematically with fire safety issues. Performing evacuation drills or exercises in a key part in training the relevant persons to be able to handle an evacuation in a good way. As an evacuation exercise usually includes the participation of a number of persons it is necessary to plan for the exercise in order to get value for the time spent. Therefore, the purpose of the exercise must be clearly stated in order to avoid waste of expensive time.

Basically two types of evacuation exercises can be identified; a fully informed training exercise and the uninformed evacuation exercise. Both have their own purposes and preferably they should be combined, but not simultaneously.

A fully informed training exercise is more like an education activity where the purpose is to show how to act in case an evacuation must be performed. The exercise consists of walking along the escape routes, checking the facilities for evacuation and refuge, etc. If necessary the exercise can be combined with the use of artificial smoke to enhance the degree of reality. This form of exercise is usually part of a fire training program.

The uninformed evacuation exercise is supposed to test what happens during a simulated real fire. Preferably, this exercise follows a more formal training in order to be beneficial for all persons involved. In most cases no information is given to the participants that an exercise is going to be performed. The exercise starts with a simulated fire, which is carefully designed in terms of smoke and visual effects. It must be located in a way that meets the objectives of the test. The exercise continues with the normal procedures that have to be conducted in the case of a real fire. This means that the persons shall act as they are supposed in case of a fire.

In order to use the results from an unannounced evacuation a documentation of the exercise is necessary. In most cases video recordings at certain locations can provide important information for a review of the exercise. One obvious problem is to combine the use of cameras with the use of artificial smoke and darkness. Usually most video cameras can film in the infrared part of the spectrum or certain heat sensing cameras can be used. Finally, when the persons taking part in the exercise exit the tunnel a questionnaire can be used to let the persons share their experiences by answering questions and write their own comments about the outcome of the exercise. In the next paragraphs an outline of a check-list for the unannounced evacuation exercise is provided.

Preparation

- What is the purpose with the exercise? What is going to be investigated? As the exercise is unannounced, think about possible outcomes.
- Where shall the simulated fire be located and why at that location? What is the fire scenario the exercise is going to simulate?
- What is to be observed?
- Limitation of the physical area included in the exercise?
- How is the exercise initiated?
- How is the exercise terminated and how to return to normal conditions?
- Information to key persons within the organisation and outside (alarm call centre, fire department).
- What happens if something goes wrong?
- How shall the exercise be documented?
    - video cameras
    - observers
    - questionnaires
    - interviews with participants

Performing the exercise

- Who initiates the simulated fire?
- Who starts the cameras?
- What happens if something goes wrong?
- Who takes care of the persons arriving to the safe location (if necessary)?
- Administration of questionnaires?
- Official closure of the test and how to return to normal conditions?

After the test

- Information to all participants directly after the exercise. Provides a good education opportunity.
- Management of persons not feeling well after the exercise?
- Removing of equipment related to the exercise?
- Preparation of documentation of the exercise?
- Reporting the test. Information forwarded to the next exercise?

Appendix B, Questionnaire used at the TBM drill

En

Example of questionnaire used in an evacuation exercise.

Aim of the questionnaire

The purpose with this questionnaire is to investigate how you and your colleagues experience a fire situation in the TBM. This is done in order to be able to improve fire and evacuation safety in tunnel construction sites. Another purpose is to identify possible difficulties during an evacuation.

1. You have just taken part in an evacuation drill. How did you first note that something unusual had happened? (More than one option may be applicable)

- ☐ I saw smoke
- ☐ I saw other people in the TBM that were not supposed to be there
- ☐ Someone told me
- ☐ I heard the fire alarm
- ☐ I got a message over the radio
- ☐ Other, namely:____

2. What did you do when you first noted that something unusual had happened? (More than one option may be applicable)

- ☐ I went towards the rescue chamber
- ☐ I spoke with a colleague
- ☐ I used my radio
- ☐ I went to see what had happened
- ☐ I put on my safety mask
- ☐ I went to get a fire extinguisher
- ☐ I called the security officer
- ☐ I did not do anything
- ☐ Other, namely:____

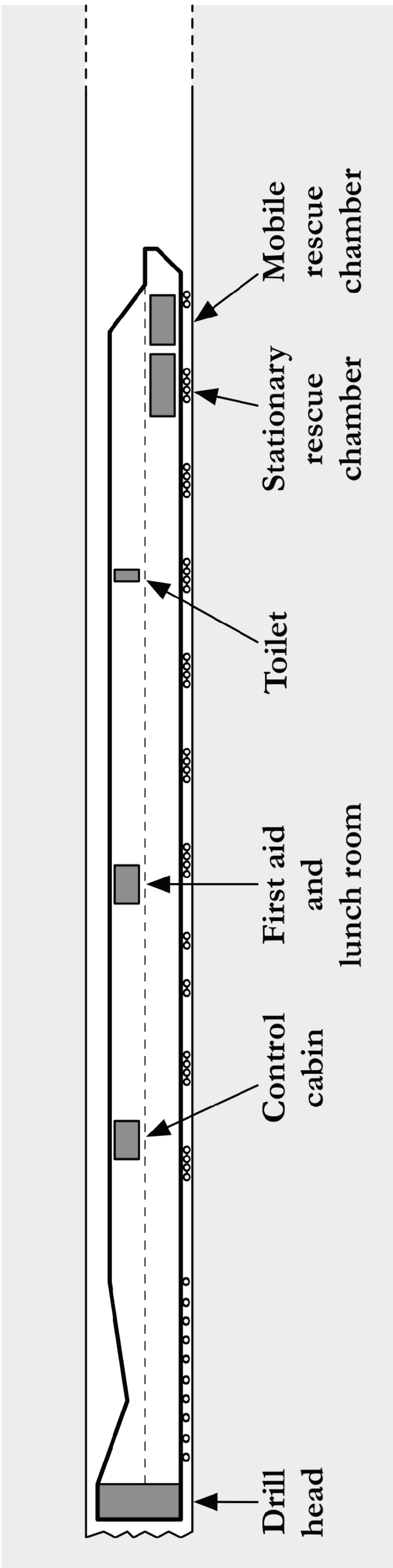
3. If you heard the fire alarm, how did it sound?

- ☐ It sounded very clear
- ☐ It sounded clear
- ☐ It sounded unclear
- ☐ It sounded very unclear

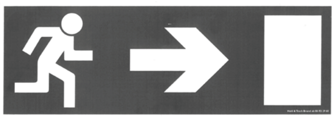
4. Did you understand the meaning of the alarm signal?

- ☐ yes, it meant____
- ☐ no

5. Where were you when you first heard the fire alarm? Mark the location on the drawing.



6. State to what extent you agree with the following statements.

	Strongly agree	Agree	Disagree	Strongly disagree	Do not know
I thought there was a fire when I heard the alarm.	☐	☐	☐	☐	☐
Evacuation drills are unnecessary.	☐	☐	☐	☐	☐
I thought it was a drill when I heard the alarm.	☐	☐	☐	☐	☐
Evacuation drills take unnecessary much time to perform.	☐	☐	☐	☐	☐
I thought an accident had occured when I heard the alarm.	☐	☐	☐	☐	☐
I thought something wrong with the TBM when I heard the alarm.	☐	☐	☐	☐	☐
Fire drills take unnecessary much time to perform.	☐	☐	☐	☐	☐
Tidyness is necessary for fire safety.	☐	☐	☐	☐	☐
I thought the tunnel had caved in when I heard the alarm.	☐	☐	☐	☐	☐
I thought there was some electrical failure when I heard the alarm.	☐	☐	☐	☐	☐
Signs (se below) indicating the routes to the rescue chamber are not necessary. 	☐	☐	☐	☐	☐
I thought something was wrong with the alarm when I heard the alarm.	☐	☐	☐	☐	☐
I thought it was a false alarm when I heard the alarm.	☐	☐	☐	☐	☐
Evacuation drills are necessary.	☐	☐	☐	☐	☐
I thought something serious had happened when I heard the alarm.	☐	☐	☐	☐	☐
Evacuation drills are a good way to practice.	☐	☐	☐	☐	☐

7. Did you experience any particular problems during the evacuation? (describe below)

____

____

____

- -

8. I am

- ☐ Male
- ☐ Female

9. I am born in19__________

10. I grew up in (state the country):_______________________________________

11. I can speak and understand the following languages (More than one option may be applicable):

- ☐ Swedish
- ☐ German
- ☐ English
- ☐ French
- ☐ Polish
- ☐ other:____

12. Do you have any experience of any of the following (except from today's drill)? (More than one option may be applicable)

- ☐ A real fire evacuation from a building, tunnel, ship or similar
- ☐ Taken part in a fire exercise under controlled conditions
- ☐ Tried to extinguish a fire under controlled conditions
- ☐ Experienced any serious event (like trapped in an elevator, a "near miss" accident or similar)

Describe the situation:

____

____

____

13. Have you ever practiced sitting (several hours) in a rescue chamber?

- ☐ yes
- ☐ no

Appendix C, Results from the TBM drill

Investigation of attitudes among the TBM tunnel workers in the Hallandsås tunnel. The results are separated for persons staying together in the mess room and persons who were at other locations when the evacuation commenced.

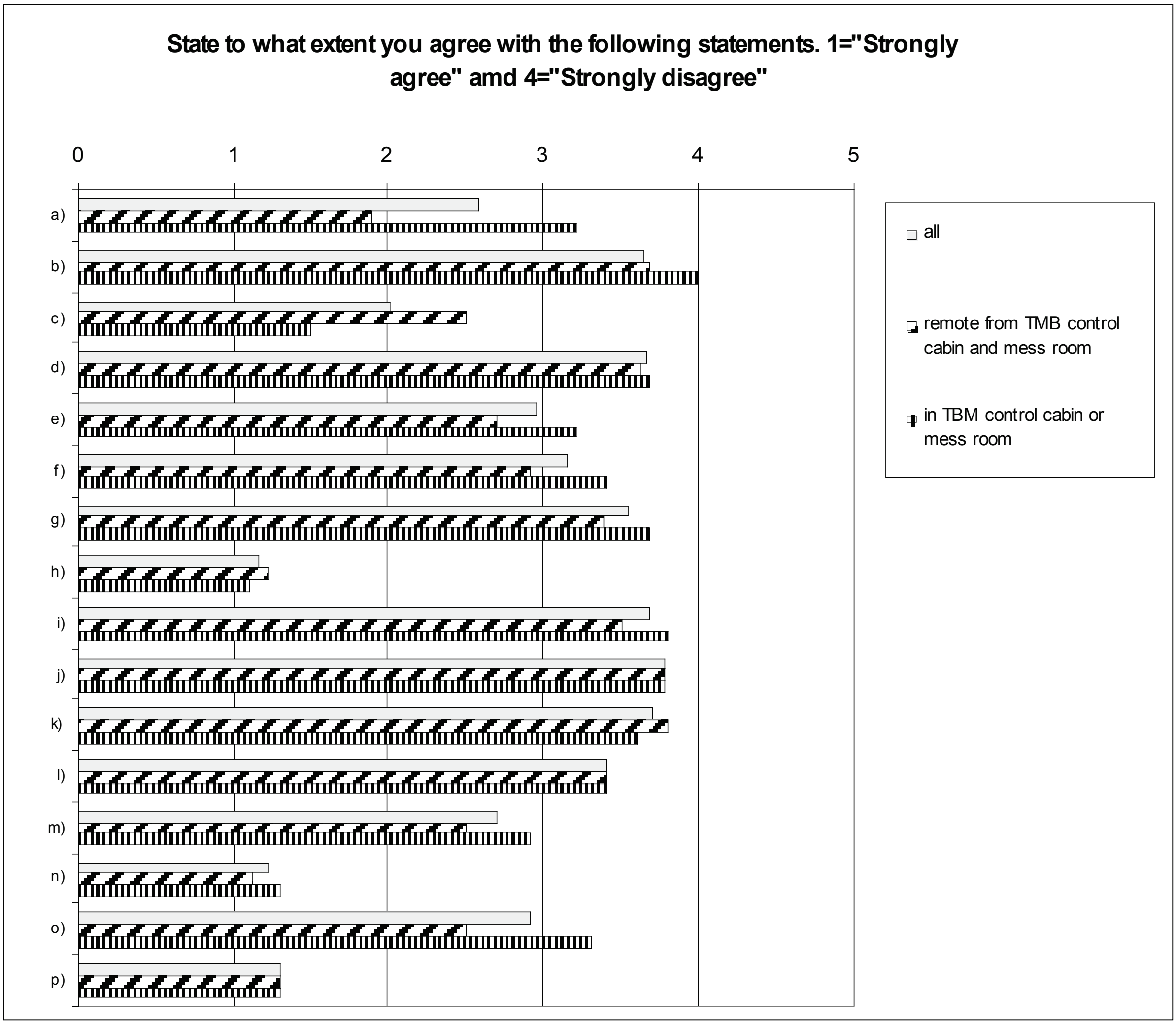


Figure C1. Questionnaire results from TBM evacuation. The statements are presented in table C1 below.

Table C1. Questionnaire statements for the experiment in Hallandsås tunnel.

Statements
a) I thought there was a fire when I heard the alarm.
b) Evacuation drills are unnecessary.
c) I thought it was a drill when I heard the alarm.
d) Evacuation drills take unnecessary much time to perform.
e) I thought an accident had occurred when I heard the alarm.
f) I thought something wrong with the TBM when I heard the alarm.
g) Fire drills take unnecessary much time to perform.
h) Tidiness is necessary for fire safety.
i) I thought the tunnel had caved in when I heard the alarm.
j) I thought there was some electrical failure when I heard the alarm.
k) Signs (se below) indicating the routes to the refuge chamber are not necessary.
l) I thought something was wrong with the alarm when I heard the alarm.
m) I thought it was a false alarm when I heard the alarm.
n) Evacuation drills are necessary.
o) I thought something serious had happened when I heard the alarm.
p) Evacuation drills are a good way to practice.

Appendix D, Matlab model assumptions and equations

The model is used to derive the time and distance for the workers to move in the tunnel before they are incapacitated by the smoke contents. The model is one-dimensional which imply that the conditions are equal at a certain distance from the fire and at a certain time. The variation across the tunnel cross section is assumed to be of little importance compared to the variation along the tunnel. The parameters derived by the fire calculations are, as a function of time and distance from the fire:

- temperature
- concentration of carbon monoxide
- concentration of carbon dioxide
- concentration of oxygen
- visibility

These environmental parameters are derived using the expressions derived in Ingason (2005). The main input variable into these equations are the heat release rate (HRR) but also other parameters have to be specified. The so called default values used for the calculations are;

- soot yield, y_s = 0,15 g smoke/g fuel
- CO_2 yield, y_{CO2} = 2,5 g/g
- CO yield, y_{CO} = 0,05 g/g
- heat of combustion, ΔH_c = 30 MJ/kg
- heat transfer coefficient, h_{tot} = 0,03 kW/m^{2}K

As long as the persons are moving away from the fire in the smoke filled tunnel they are exposed to the conditions along this walk. The persons are able to continue to walk as long as the untenable conditions due to toxic accumulation have been reached. Several limits are used for the analysis and those are presented in chapter 6 in this report. When the toxic level leading to unconsciousness are reached the persons will continue to accumulate the toxic contents of the smoke but at a lower rate. Finally, lethal levels may be reached.

The calculations are performed in time steps of 30 seconds. The conditions for each time step are evaluated at 15 seconds into each time step assuming that the conditions will not change significantly within each time step.

Algorithm

A simplified procedure for the calculation is presented below.

Introduction

The persons are initially located at distance StartDist from the fire. The persons are assigned a pre-movement delay time. The time is assumed to be expressed in minutes.

The exposure of the persons starts after the pre-movement time and with exposure levels relevant for the location StartDist.

Exposure

Calculate the HRR value for the present location and time. Adjust for the smoke transportation time.

Calculate the smoke temperature for the present location and time.

Calculate the concentrations of CO, CO_2, O_2 and smoke particles for the present location and time.

Toxic dose for unconsciousness

Calculate the fractional effective dose component for the time step for each of the gases CO, CO_2, O_2 and temperature: F_{CO}, F_{CO2}, F_{O2}, F_{temp}.

$$F_{CO} = \frac{K(koncCO^{1,036})t}{30}$$

using a critical carboxyhemoglobin (COHb) level of 30 % and

$$K = 8,2925*10^{-4}$$

$$F_{CO2} = \frac{1}{e^{(6,1623-0,5189\, koncCO_2)}} t$$

$$F_{O2} = \frac{1}{e^{8,13-0,54(20,9-koncO2)}} t$$

$F_{temp} = \frac{1}{e^{5,18-0,0273T}} t$ if the smoke temperature is above 37 °C.

Calculate the total fractional incapacitating dose for the combined effect of the gases. Adjust for the increased breathing rate due to the CO_2-level, V_{CO2}. Add the component caused by low oxygen level.

$$FID = F_{CO} \cdot V_{CO2} + F_{O2}$$

using

$$VCO_2 = \frac{e^{2,0004+0,1903 koncCO_2}}{7,1}$$

Walking speed

Calculate the visibility and derive the walking velocity according to the solid bold line in figure D1. Derive the advancement using this velocity for the current time step unless the incapacitation level has been reached.

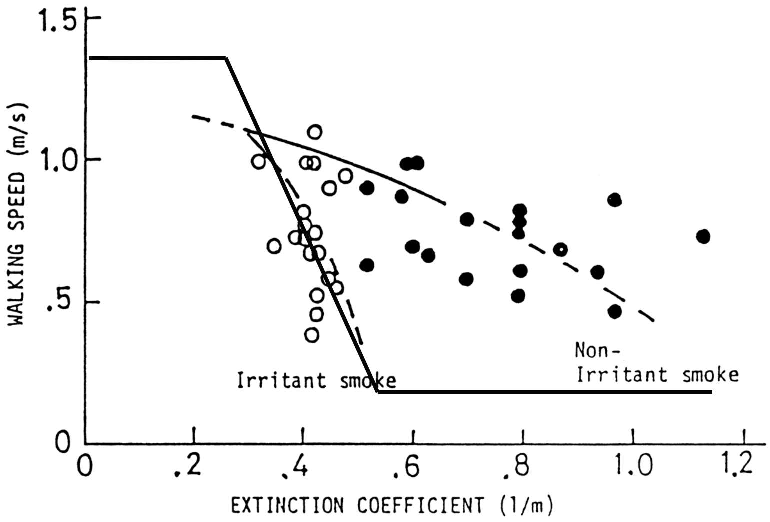


Figure D1. Walking velocity as a function of smoke density (Jin & Yamada, 1985). The bold solid line is used in the evacuation model to determine the current speed.

Toxic dose for lethal conditions

Calculate the fractional lethal dose for the CO concentration

$$F_{LCO} = \frac{K(koncCO^{1,036})t}{50}$$

using a critical carboxyhemoglobin (COHb) level of 30 % and

$K = 8,2925 * 10^{-4}$ if the person is conscious

$K = 1,99 * 10^{-4}$ if the person is unconscious

Calculate the total fractional lethal dose for the combined effect of the gases. Adjust for the increased breathing rate due to the CO_2-level, V_{CO2}. Add the component caused by low oxygen level.

$$FLD = F_{LCO} \cdot V_{CO2} + F_{O2}$$

If the oxygen concentration is below 8,7 vol% an acute lethal condition occurs.

Storage of accumulated values

Derive the accumulated values for

- *FID*
- F_{temp}
- F_{CO2}
- *FLD*
- Walking distance from the location of the fire

Check if unconsciousness has occurred. If so, assign a lower breathing rate and stop the physical advancement in the tunnel. Unconsciousness occurs if the fractional incapacitating dose is > 1,0 for the combined effect of inhaled gases, temperature or carbon dioxide.

Repeat for the following time step until the maximum allowed time has reached, normally 120 minutes.

Fire development

The model for evacuation need and analytical expression of the fire curve, i.e. the HRR development. The background information of the fires may be found in Ingason, Lönnermark, Frantzich & Kumm (2010).

The HRR is derived using the following expression:

$$\dot{Q}(t) = \left(\dot{Q}_{\max,1} \cdot n_1 \cdot r_1 \cdot (1 - e^{-k_1 \cdot t})^{n_1 - 1} \cdot e^{-k_1 \cdot t} + \dot{Q}_{\max,1} \cdot n_2 \cdot r_2 \cdot (1 - e^{-k_2 \cdot t})^{n_2 - 1} \cdot e^{-k_2 \cdot t} \right) \quad (2)$$

where $k_1 = \frac{\dot{Q}_{\max,1}}{E_{tot,1}} \cdot r_1$ and $k_2 = \frac{\dot{Q}_{\max,2}}{E_{tot,2}} \cdot r_2$ and $r_1 = \left(1 - \frac{1}{n_1}\right)^{1-n_1}$ and $r_2 = \left(1 - \frac{1}{n_2}\right)^{1-n_2}$

The factor n is used for controlling the growth rate of the fire and is a result of an curve fitting procedure. The values used for the calculations are provided in Table D1.

Table D1. Values defining the HRR curves

Fire scenario	**Q1max**	**Q2max**	**Etot,1**	**Etot,2**	**n1**	**n2**
	MW	MW	MJ	MJ	-	-
Drilling rig	6	-	27 000	-	4	-
Two pass. cars	8	-	14 200	-	2,1	-
Art. hauler	3	12,5	3 000	78 000	2,9	4,3
Bus	30	-	40 000	-	4	-

Appendix E, Sensitivity analysis using the Matlab model.

The appendix shows all the results from the sensitivity analysis. Some of the material can also be found in the main part of the report. In the comments field a reference is made to a constant n1. This is a constant that changes the increase rate of the HRR-curve. A lower value of n1 results in a faster development of the fire. The default values for the four fire scenarios are found in Appendix D.

Fire in most remote part of tunnel

Fire in a bore rig max 6 MW

wind velocity	cross section	Rec&Res time	Startdist	FED_max	FED=0,3 distance	FED=0,3 Time	FED=1 distance	FED=1 time	FLD=1 time	comments
m/s	m2	s	m	-	m	minutes	m	minutes	minutes or max FLD	
0,5	3x4	60	50	0			1700	23		
0,5	3x4	200	50	0			1700	23		
0,5	3x4	200	0	0			1700	23		
1	3x4	200	0	0			1700	23		
0,5	3x4	240	0	1			430	40		
0,5	3x4	300	0	1			410	38		
0,5	3x4	300	50	0			1700	25		
1	3x4	300	0	1			550	50		
1	3x4	300	50	0			1700	26		
1,5	3x4	300	0	1			840	69		
0,5	3x4	400	0	1			380	38		
0,5	3x4	400	50	1			460	40		
1	3x4	400	0	1			530	50		
1	3x4	400	50	1			590	51		
0,5	4x5	300	0	1			560	51		
1	4x5	300	0	0			1700	23		
1	4x5	400	0	1			830	76		
1,5	4x5	400	0	0,9			1400	120		
0,5	5x5	300	0	1			660	60		
1	5x5	300	0	0			1700	23		
1	5x5	400	0	1			1290	99		
1,5	5x5	400	0	0,7			1500	120		
0,5	6x7	300	0	0			1700	25		
1	6x7	300	0	0			1700	23		
1	6x7	400	0	0			1700	27		
0,5	6x7	900	300	0			1700	27		walks in thin smoke (good visibility and no big problems
0,5	7x11	200	50	0			1700	23		moves ahead of smoke front but not initially
0,5	7x11	200	0	0			1700	24		moves ahead of smoke from after a few minutes
0,5	7x11	200	0	0			1700	25		n1=3
0,5	7x11	200	50	0			1700	24		n1=3
1	7x11	200	50	0			1700	23		

Figure E1. Evacuation results from fire in the drilling rig.

Fire in most remote part of tunnel

Fire in a bore rig max 6 MW

wind velocity	cross section	Rec&Res time	Startdist	FED_max	FED=0,3 distance	FED=0,3 Time	FED=1 distance	FED=1 time	FLD=1 time	comments
m/s	m2	s	m	-	m	minutes	m	minutes	minutes or max FLD	
0,5	7x11	400	50	0			1700	23		moves ahead of smoke from after a few minutes
0,5	7x11	400	50	0			1700	27		n1=3,5
0,5	7x11	400	0	0,8			1360	120		n1=3,5
0,5	7x11	400	0	0			1700	27		
0,5	7x11	400	50	0,8			1412	120		n1=3
1	7x11	400	50	0,35			1460	120		n1=3
1	7x11	400	0	0,35			1365	120		n1=3
0,5	7x11	600	50	0,8			1700	120		0,2 m/s walking speed in smoke
0,5	7x11	600	0	0,8			1350	120		
0,5	7x11	600	50	0,8			1370	120		n1=3,5
1	7x11	600	50	0,2			1700	90		1 m/s in the beginning and 0,2 when in smoke
1	7x11	600	50	0,2			1700	90		
0,5	3x4	300	50	0	>1700	120	>1700	120	max=0,0 at 120 min	
0,5	4x5	300	50	0	>1700	120	>1700	120	max=0,0 at 120 min	
0,5	5x5	300	50	0	>1700	120	>1700	120	max=0,0 at 120 min	
0,5	6x7	300	50	0	>1700	120	>1700	120	max=0,0 at 120 min	
0,5	7x11	300	50	0	>1700	120	>1700	120	max=0,0 at 120 min	
0,5	3x4	660	50		236	26,5	380	38,5	49	Rec&resp time determined by HRR=1 MW
0,5	4x5	660	50		308	32,5	530	51	84	Rec&resp time determined by HRR=1 MW
0,5	5x5	660	50		350	36	614	58,5	max=0,95 at 120 min	Rec&resp time determined by HRR=1 MW
0,5	6x7	660	50		470	46	926	84,5	max=0,71 at 120 min	Rec&resp time determined by HRR=1 MW
0,5	7x11	660	50		674	63	>1700	120	max=0,47 at 120 min	Rec&resp time determined by HRR=1 MW
1	3x4	660	50		296	31,5	524	51	max=0,96 at 120 min	
1	4x5	660	50		398	40	836	77	max=0,7 at 120 min	
1	5x5	660	50		596	56,5	1118	100,5	max=0,65 at 120 min	
1	6x7	660	50		677	60,5	>1700	120	max=0,4 at 120 min	
1	7x11	660	50		1208	103	>1700	120	max=0,2 at 120 min	

Figure E2. Evacuation results from fire in the drilling rig.

Fire in most remote part of tunnel

Fire in twp passenger cars max 8 MW

wind velocity	cross section	Rec&Res time	Startdist	FED_max	FED=0,3 distance	FED=0,3 Time	FED=1 distance	FED=1 time	FLD=1 time	comments
m/s	m2	s	m	-	m	minutes	m	minutes	minutes or max FLD	
0,5	3x4	60	50	0			1700	21		
0,5	3x4	200	50	1			134	10		
0,5	3x4	200	0							
1	3x4	200	0	1			0			
0,5	3x4	240	0							
0,5	3x4	300	0							
0,5	3x4	300	50							
1	3x4	300	0							
1	3x4	300	50							
1,5	3x4	300	0							
0,5	3x4	400	0							
0,5	3x4	400	50							
1	3x4	400	0							
1	3x4	400	50							
0,5	4x5	300	0	1			0			
1	4x5	300	0							
1	4x5	400	0							
1,5	4x5	400	0							
0,5	5x5	300	0	1			0			
1	5x5	300	0							
1	5x5	400	0							
1,5	5x5	400	0							
0,5	6x7	300	0							
1	6x7	300	0							
1	6x7	400	0							
0,5	6x7	900	300							
0,5	7x11	200	50	0,6			1700	118		
0,5	7x11	200	0	0,6			1700	118		

Figure E3. Evacuation results from fire in the two passenger cars.

Fire in most remote part of tunnel

Fire in twp passenger cars max 8 MW

wind velocity	cross section	Rec&Res time	Startdist	FED_max	FED=0,3 distance	FED=0,3 Time	FED=1 distance	FED=1 time	FLD=1 time	comments
m/s	m2	s	m	-	m	minutes	m	minutes	minutes or max FLD	
1	7x11	200	50	0,2			1700	83		
0,5	7x11	400	50	0,55			1700	118		
0,5	7x11	400	50							
0,5	7x11	400	0	0,55			1700	118		
0,5	7x11	400	0							
0,5	7x11	600	50	0,5			1700	118		
0,5	7x11	600	0							
0,5	7x11	600	50							
1	7x11	600	50							
0,5	7x11	400	50							
1	7x11	400	50							
1	7x11	600	50							
1	7x11	400	0							
0,5	7x11	60	0	0,6			1700	118		
0,5	7x11	60	50	0			1700	21		
0,5	3x4	120	50		116	7,5	164	11,5	13,5	
0,5	4x5	120	50		152	10,5	248	19	72	FLD=0,9 at 35 minutes i.e. flat curve
0,5	5x5	120	50		176	12,5	314	24	max=0,8 at 120 min	
0,5	6x7	120	50		242	18	680	55	max=0,66 at 120 min	
0,5	7x11	120	50		398	31	>1700	max 0,6	max=0,38 at 120 min	
1	3x4	120	50		146	10	278	21	max=0,82 at 120 min	
1	4x5	120	50		206	15	>1700	max 0,95	max=0,61 at 120 min	
1	5x5	120	50		254	19	>1700	max 0,74	max=0,47 at 120 min	
1	6x7	120	50		458	36	>1700	max 0,41	max=0,26 at 120 min	
1	7x11	120	50		>1700	max 0,21				

Figure E4. Evacuation results from fire in the two passenger cars.

Fire in most remote part of tunnel

Fire in an articulated hauler max 12,5 MW

wind velocity m/s	cross section m2	Rec&Res time s	Startdist m	FED_max -	FED=0,3 distance m	FED=0,3 Time minutes	FED=1 distance m	FED=1 time minutes	FLD=1 time minutes or max FLD	comments
0,5	3x4	60	50	0			1700	21		starts before smoke front reaches initial location
0,5	3x4	60	5	1			300	25		
0,5	3x4	120	5	1			280	25		
0,5	3x4	200	50	1			326	26		
0,5	3x4	200	0	1			252	24		
0,5	3x4	240	5	1			250	24		
0,5	3x4	300	5	1			245	25		fld=2
0,5	3x4	300	50	1			302	26		
1	3x4	300	5	1			420	40		
1	3x4	300	50	1			470	40		
1,5	3x4	300	5	1			520	48		
0,5	3x4	400	5	1			5	0		fld=2
0,5	3x4	400	50	1			290	26		
1	3x4	400	5	1			400	40		
0,5	4x5	300	5	1			419	39		
1	4x5	300	5	1			581	53		
1	4x5	400	5	1			563	54		
1,5	4x5	400	5	1			710	65		
0,5	5x5	300	5	1			500	46		
1	5x5	300	5	1			670	61		
1	5x5	400	5	1			650	60		
1,5	5x5	400	5	1			830	75		
0,5	6x7	300	5	1			695	62		
1	6x7	300	5	1			960	85		
1	6x7	400	5	1			940	85		
0,5	7x11	200	50	1			1120	92		
1	7x11	200	50	0,8			1450	120		
0,5	7x11	200	5	1			1040	90		

Figure E5. Evacuation results from fire in the articulated hauler.

Fire in most remote part of tunnel

Fire in an articulated hauler max 12,5 MW

wind velocity m/s	cross section m2	Rec&Res time s	Startdist m	FED_max -	FED=0,3 distance m	FED=0,3 Time minutes	FED=1 distance m	FED=1 time minutes	FLD=1 time minutes or max FLD	comments
0,5	7x11	400	50	1			1064	91		
0,5	7x11	600	50	1			1010	90		
1	7x11	600	50	0,8			1370	120		
0,5	7x11	600	5	1			940	88		
1	7x11	120	5	0,8			1430	120		
1	7x11	120	50	0			1700	22		
0,5	7x11	60	5	0			1700	21		
0,5	7x11	120	5	1			1070	91		
0,5	7x11	120	50	0			1700	22		
0,5	3x4	300	50		146	13	302	26,6	38,5	
0,5	4x5	300	50		224	19,5	482	41,5	56,5	
0,5	5x5	300	50		272	23,5	566	48	65,5	
0,5	6x7	300	50		416	35,5	764	65	99	
0,5	7x11	300	50		614	52	1088	92	max = 0,75 at 120 min	
0,5	3x4	240	50		158	13	320	26,5	39	
0,5	6x7	240	50		434	36	782	65,5	99	
0,5	7x11	240	50		626	52	1106	92	max = 0,75 at 120 min	
0,5	3x4	180	50		175	13,5	332	27	39,5	
0,5	6x7	180	50		446	36	800	66	100	
0,5	7x11	180	50		644	52,5	1124	93	max = 0,75 at 120 min	
0,5	3x4	120	50		194	14	356	27,5	40	
0,5	6x7	120	50		1700	22	1700			
0,5	7x11	120	50		1700	22	1700			
1	3x4	300	50		248	21,5	470	40,5	54,5	
1	6x7	300	50		560	47,5	1016	86	0,74	
1	7x11	300	50		770	65	1700	0,78	0,5	
1	3x4	120	50		278	21	512	40,5	55	

Figure E6. Evacuation results from fire in the articulated hauler.

Fire in most remote part of tunnel

Fire in a bus max 30 MW

wind velocity m/s	cross section m2	Rec&Res time s	Startdist m	FED_max -	FED=0,3 distance m	FED=0,3 Time minutes	FED=1 distance m	FED=1 time minutes	FLD=1 time minutes or max FLD	comments
0,5	4x5	300	0	1			0	0		High radiation levels close to fire. Use Startdist = 50 m
0,5	4x5	300	50	1			100	9		
1	4x5	300	50	1			122	11		
1	4x5	400	50	1			104	11		
1,5	4x5	400	50							
0,5	5x5	300	0	1			0	0		
1	5x5	300	50	1			146	13		
1	5x5	400	50	1			128	13		
1,5	5x5	400	50	1			104	11		
0,5	6x7	300	0							
1	6x7	300	50	1			260	22		
1	6x7	400	50	1			242	22		
1,5	6x7	400	50	0,82			242	79		
0,5	7x11	60	50	0						
0,5	7x11	60	5	0						
1	7x11	60	50	0						
1,5	7x11	60	50	0,4						
1,5	7x11	60	5	0,4						
0,5	7x11	200	50	1			284	23		High rate of rise of FED-curve
0,5	7x11	200	0	1			204	20		
0,5	7x11	200	50	0						n1=6
1	7x11	200	50	0,72				84		
0,5	7x11	240	50	0			1700	24		n1=6
0,5	7x11	300	50	1			308	27		n1=6

Figure E7. Evacuation results from fire in the bus.

Fire in most remote part of tunnel

Fire in a bus max 30 MW

wind velocity m/s	cross section m2	Rec&Res time s	Startdist m	FED_max -	FED=0,3 distance m	FED=0,3 Time minutes	FED=1 distance m	FED=1 time minutes	FLD=1 time minutes or max FLD	comments
0,5	7x11	400	50	1			230	21		High rate of rise of FED-curve
0,5	7x11	400	50	1			278	25		n1=6
1	7x11	400	50	0,7				84		
0,5	7x11	600	50	1			194	22		High rate of rise of FED-curve
0,5	7x11	600	0	1			0	25		High radiation levels close to fire.
1	7x11	600	50	0,6				84		Worst conditions passed when evacuation starts
1	7x11	600	300	0,7				84		This scenario corresponds to fire in another bus
1,5	7x11	60	0	0			1700	24		n1=6
1	7x11	200	50	0			1700	24		n1=6
0,5	7x11	400	50	1			278	25		n1=6
1	7x11	400	50	0,7				85		n1=6
1	7x11	300	50	0,7				85		n1=6
1,5	7x11	300	50	0,4				75		n1=6
0,5	3x4	150	50	-	-	-	-	-	-	
0,5	4x5	150	50		128	9	146	10,5	10,5	
0,5	5x5	150	50		134	9,5	158	12	12	
0,5	6x7	150	50		164	12	206	15,5	17,5	
0,5	7x11	150	50		>1700	120	>1700	120	max = 0	thin smoke so persons can move away from smoke front
0,5	7x11	180	50		194	15	296	24	max=0,9	
0,5	7x11	240	50		176	14,5	278	23	max=0,9	

Figure E8. Evacuation results from fire in the bus.