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Fire evacuation in underground transportation systems: a review of accidents and empirical research

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Fire evacuation in underground transportation systems: a review of accidents and previous research

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Utrymning i transportsystem under mark vid brand: en granskning av tidigare olyckor och forskning
Fire evacuation in underground transportation systems: a review of accidents and research

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Abstract
A review of literature related to fire evacuation in underground transportation systems, e.g., tunnels and subway stations, was carried out with the objectives (1) to identify a theoretical framework that can help understand of human behaviour in the event of a fire in underground transportation systems, (2) to use the theoretical framework to analyse and to identify problems related to fire evacuation in underground transportation systems, and (3) to suggest areas on which future research should focus on in. The review included literature on past accidents in underground transportation systems, theories and models on human behaviour in fire, and empirical research. It was concluded that the adoption of a clear theoretical framework can aid the understanding of people's behaviour in the event of a fire in underground transportation systems, and that a behaviour that seems irrational to an outside observer seldom is. The theoretical framework should include the behaviour sequence model, the affiliative model, social influence, and the theory of affordances. It was also concluded that one of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate evacuation, which among other things is explained with a role keeping behaviour, lack of information, ambiguity of fire cues and the presence of others, i.e., social influence. Other factors that affect the actual movement of people in underground transportation systems were identified as problems with the door-opening mechanisms on trains, the vertical distance between train and tunnel floor, that people tend to evacuate through familiar exits, the lack of lighting, and uneven surfaces inside tunnels. The review demonstrated that there are room for improvements in the area of fire evacuation in underground transportation systems, and future research should among other things study the effects of a comprehensive evacuation system, the optimal design of active systems in underground transportation systems, and the possibility for people with disabilities to evacuate from these types of facilities.

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Summary

In recent year the number of rail and road tunnels has increased, and today the possibility to travel underground is taken for granted by most people. In addition, the average of length of the tunnels has increased in recent years. The demand on society to handle fire and evacuation safety in these types of facilities, which in this report is termed underground transportation systems, has therefore increased.

Past accidents in both rail and road tunnels illustrate that a fire in a underground transportation systems can result in devastating consequences in terms of loss of life. This is, for instance, illustrated by the fire at the King's Cross station in 1987, where 31 people were killed, by the fire in Kaprun in 2000, which claimed the lives of 155 people, and by the fire in Baku's Metro in 1995, which claimed the lives of 289 people. These, and other accidents in underground transportation systems, reveal problems related to the evacuation process.

Although there are many similarities when comparing evacuation in underground transportation systems with evacuation in a traditional building, there are also many differences that need to be acknowledged in the design phase, as well as during the operation, in underground transportation systems. By combining the observations form past accidents with conclusions from empirical research, future research areas for improving the safety in underground transportation systems can be identified.

The purpose of this report was therefore to review and to summarize literature related to fire evacuation in underground transportation systems, and to suggest areas for future research in the field. The studied literature can roughly be divided into three categories: (1) past accidents in underground transportation systems, (2) theories and models on human behaviour in fire, and (3) empirical research related to evacuation in underground transportation systems.

It was concluded that human behaviour in fire is complex and that it sometimes can seem irrational to a person studying the behaviour in retrospect. But instead of using 'panic' to describe the human behaviour and the outcome of an accident, the adoption of a clear theoretical framework could aid the understanding of people's behaviour, also in underground transportation systems. This theoretical framework should include the behaviour sequence model, the affiliative model, social influence and the theory of affordances.

One of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. This is explained by a number of factors:

- That people tend to maintain their roles (e.g., as passengers)
- The lack of fast, clear and coherent information
- The ambiguity of the cues from the source of danger (e.g., a fire)
- The presence of others, i.e., social influence

Furthermore, when an evacuation has been initiated there are other factors that affect the efficiency of the evacuation. Some of the problems that was identified are:

- Problems with the door-opening mechanism on trains
- The vertical distance between the train and the tunnel floor
- That people tend to evacuate through familiar exits
- Lack of lighting
- Uneven surfaces inside the tunnels

In order to improve the safety for users of underground transportation systems, it is suggested that future research should:

- Study the effects of a comprehensive evacuation system that involves traffic information signs and TV screens, directive public announcements through public announcement systems, and involvement of the staff
- Study the optimal design of active systems in order to break the affiliative behaviour of tunnel occupants
- Study the possibility for people with disabilities to evacuate from tunnels
- To study the effects of different surface types in a tunnel and to compare the results in a cost-benefit analysis
- To study the effects of implementing continuous training, education and drills for staff working in tunnels and to compare the results in a cost-benefit analysis

Sammanfattning

På senare år har antalet väg- och järnvägstunnlar ökat i antal, och möjligheten att resa under mark tas idag för givet av de flesta människor. Samtidigt har medellängden av världens tunnlar ökat. Det har lett till att kravet på samhället att hantera bränder och utrymningssäkerhet i den här typen av anläggningar, vilka i den här rapportens benämns transportsystem under mark, har ökat.

Tidigare inträffade olyckor i både väg- och järnvägstunnlar visar att en brand i ett transportsystem under mark kan leda till förödande konsekvenser vad gäller antal döda. Detta exemplifieras bland annat av branden på King's Cross-stationen 1987, där 31 människor omkom, av branden i Kaprun 2000 vilken tog livet av 155 människor, samt av branden i Bakus tunnelbana som krävde 289 människoliv. Dessa, och andra olyckor som inträffat i transportsystem under mark, visar på att det finns problem relaterade till utrymningsprocessen i denna typ av anläggningar.

Även om det finns många likheter i jämförelsen mellan utrymning från transportsystem under mark och utrymning från en traditionell byggnad, så finns det också många skillnader som måste beaktas både i designskedet och i driftskedet av transportsystem under mark. Genom att kombinera observationer från tidigare olyckor och slutsatser från empirisk forskning kan problemområden identifieras som framtida forskning bör fokusera på för att öka säkerheten i transportsystem under mark.

Syftet med denna rapport har därför varit att undersöka och sammanfatta litteratur relaterad till utrymning i transportsystem under mark, samt att föreslå framtida forskningsområden i ämnet. Lite grovt kan den studerade litteraturen delas in i tre kategorier: (1) tidigare inträffade olyckor i transportsystem under mark, (2) teorier och modeller inom mänskligt beteende vid brand, och (3) empirisk forskning relaterad till utrymning i transportsystem under mark.

I denna rapport drogs slutsatsen att mänsklig beteende i bränder är komplext, och att det ibland kan uppfattas som irrationellt när det studeras i efterhand. Men istället för att använda ordet "panik" för att beskriva det mänskliga beteendet i, och konsekvensen av, en olycka, kan användandet av ett tydligt teoretisk ramverk underlätta förståelsen av mänskligt beteende vid brand, även i transportsystem under mark. Detta teoretiska ramverks bör innehålla den så kallade beteendesekvensmodellen, anknytningsmodellen, social påverkan samt teorin om *affordances*.

Ett av de största problemen som identifierats är att människor ofta är motvilliga till att inleda en utrymning vid brand i ett transportsystem under mark. Detta kan förklaras av ett antal faktorer:

- Att människor tenderar att behålla sina roller (till exempel som passagerare i tunnelbanan)
- Brist på snabb, tydlig och sammanhängande information
- Tvetydiga signaler från faran (till exempel branden)
- Närvaron av andra människor, så kallad social påverkan

Dessutom identifierades ett antal faktorer som påverkar effektiviteten av utrymningsförloppet. Några av de problem som identifierades är:

- Problem med dörröppningsmekanismen på tåg
- Den vertikala höjdskillnaden mellan tåg och tunnelgolv
- Att människor tenderar att utrymma via välkända utgångar
- Brist på ljus
- Ojämna markytor i tunneln

För att öka säkerheten för användare av transportsystem under mark föreslås det att framtida forskning bör fokusera på:

- Att studera effekterna av ett heltäckande utrymningssystem som omfattar trafikinformationsskyltar och TV-skärmar, instruktioner via talade meddelanden i högtalare och involvering av personal som jobbar i tunnlarna
- Att studera den optimala designen av ett aktivt system som kan användas för att bryta invanda beteendemönster hos resenärer i tunnelbanan, till exempel att människor gärna utrymmer via välkända utgångar
- Att studera handikappades möjligheter att utrymma från tunnlar
- Att studera effekterna av olika underlag ii tunnlar och att jämföra resultaten i en kostnadsnyttoanalys
- Att studera effekterna av kontinuerlig träning, utbildning och övningar för personal som jobbar i tunnlar och att jämföra resultaten i kostnadsnyttoanalys

Preface

This work is a part of METRO, a Swedish research project about infrastructure protection. The focus of the project is on the protection of underground rail mass transport systems, e.g., tunnels and subway stations, and both fire and explosion hazards are studied.

METRO is a multidisciplinary project where researchers from different disciplines cooperate with practitioners with the common goal to make underground rail mass transport systems safer in the future. The following nine partners participate in METRO: *Mälardalen University, SP Technical Research Institute of Sweden, Lund University, Swedish Defence Research Agency (FOI), Gävle University, Swedish National Defence College, Swedish Fortifications Agency, Greater Stockholm Fire Brigade and Stockholm Public Transport (SL).*

The total budget of METRO is 14.2 million SEK (ca € 1.5 million), and the project runs over a period of three years (December 2009 to December 2012). METRO is funded by the following five organisations: *Stockholm Public Transport (SL), Swedish Civil Contingencies Agency (MSB), the Swedish Transport Administration (Transportverket), the Swedish Fortifications Agency (Fortifikationsverket), and the Swedish Fire Research Board (Brandforsk).*

The work in METRO is divided into seven work packages (WPs) which address different aspects of the studied topic:

- WP1 – Design Fires
- WP2 – Evacuation
- WP3 – Integrated Fire Control
- WP4 – Smoke Control
- WP5 – Extraordinary Strain on Constructions
- WP6 – Fire and Rescue Operations
- WP7 – Project Management

More information about METRO can be found at the following web page:

http://www.metroproject.se

This report is a part of the second work package (WP2 - Evacuation). WP2 – Evacuation is also a part of KESØ (Kompetenscentrum för evakueringssäkerhet i Öresund), which is funded by Interreg IV A (Öresund – Kattegatt – Skagerrak).

I would like to thank all the people who assisted me in the work on this report, contributing with valuable information during the writing process, especially Daniel Nilsson and Håkan Frantzich at the Department of Fire Safety Engineering and Systems Safety at Lund University.

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EUROPEISKA UNIONEN
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1. Introduction

In recent years the number of rail and road tunnels has increased, and today the possibility to travel underground is taken for granted by most people. In addition, the average length of the tunnels has, and do continue, to increase. This development has created an increased demand on society to handle fire and evacuation safety for occupants in these types of facilities, which in this report is termed underground transportation systems.

Evacuation in underground transportation systems can occur for a number of reasons, e.g., due to an electrical failure on a train or because of fire at an underground station, which in this report is regarded as part of the underground transportation system. Although there are many similarities when comparing evacuation in these types of facilities with evacuation in a traditional building, there are also many differences that need to be regarded in the design phase, as well as during the operation, of underground transportation systems. For instance, the distance to a safe location is likely to be longer, the fire load is likely to be larger and the emergency rescue services ability to assist in an emergency is smaller. In addition, tunnels are perceived as complex structures by many people (Shields, 2005). This perceived complexity is likely to increase in the event of an emergency evacuation.

Past accidents in both rail and road tunnels illustrate that a fire in an underground transportation system can result in devastating consequences in terms of loss of life. These accidents also reveal problems related to evacuation in underground transportation systems. By combining the observations from past accidents with conclusions from empirical research, future research areas for improving the safety in underground transportation systems can be identified. The purpose of this report is therefore to review and summarize literature related to fire evacuation in underground transportation systems and to suggest areas for future research in the field.

1.1. Objectives

The objectives of this report are:

1. To identify a theoretical framework that can help understand human behaviour in the event of a fire in underground transportation systems
2. To use the theoretical framework to analyse and to identify problems related to fire evacuation in underground transportation systems
3. To suggest areas on which future research should focus on in order to improve the safety in underground transportation systems

1.2. Method

In order to achieve the objectives of this report a literature review was performed. Initially, a number of keywords were defined to ensure that a systematic search in databases could be carried out. The keywords were: *human behaviour, fire, evacuation, egress, underground, tunnel, subway* and *accident*. The literature was retrieved from databases, primarily ELIN@Lund and Libris, and was complemented with relevant literature from colleagues and other publications known to the author prior to the review.

The studied literature can roughly be divided into three categories: past accidents in underground transportation systems, theories and models on human behaviour, and empirical research related to evacuation in underground transportation systems. Past accidents were studied because they illustrate clearly illustrate problems related to evacuation in underground transportation systems. Due to the fact that investigation reports often are technical, and not always include a description of the evacuation or the human behaviour, a number of topics were defined in order to facilitate the collection and reproduction of data:

- Number of deaths/injuries
- Source of the fire (where, why, how)
- Type of emergency information provided to occupants
- Type of surface on which the evacuation was carried out
- Lighting conditions
- Technical solutions related to way guidance (e.g., hand rails, exit signs, distance signs)
- Emergency services
- Human behaviour
- Ventilation

A theoretical framework for understanding human behaviour in the event of a fire in underground transportation systems is presented in the second part of this report. The theories and models have been developed to understand general human behaviour in fire, but have all been deemed valid and relevant for evacuation in underground transportation systems as well. A brief description of the theories and models are included, and experiments that have demonstrated their credibility are also included.

In the third part of this report empirical research related to evacuation in underground transportation systems is described and the results are reproduced. Empirical research were included simply because it offers important data and solutions on evacuation issues.

After the literature had been described and summarized, the data was analysed and compared. The theoretical framework was used to identify problems related to fire evacuation in underground transportation systems. The results from the analysis resulted in a discussion about evacuation issues and suggestions for future research.

1.3. Limitations

This report is a part of the second work package of the METRO project (WP2 - Evacuation), a research project that focuses on the protection of underground rail mass transport systems, such as tunnels and subway stations. Due to the fact that the literature review is carried out within the frameworks of the second work package, it mainly addresses evacuation and human behaviour in the event of fire in underground transportation systems.

Only literature considered relevant for the METRO project is included in this review. The literature is limited to past accidents in underground transportation systems, general theories and models on human behaviour in fire, and empirical research related to the chosen topic. These topics are deemed valid and relevant for fire evacuation in underground transportation systems.

2. Past accidents

Accidents that have occurred in underground transportation systems in the past, and the investigations performed afterwards, highlight problems associated with evacuation from these types of facilities. Regardless if the accident involves motor vehicles or rail bound vehicles, there are similarities regarding evacuation in underground transportation systems, therefore both types are discussed in this chapter.

The accidents are first presented and the most important observations are highlighted. Thereafter the accidents are summarized in Table 1. Finally a brief discussion is given with general conclusions about the accidents and the consequences.

2.1. Accidents in underground transportation systems for rail vehicles

In contrast to the underground transportation systems for automobiles that only consist of a road tunnel, many underground transportation systems for rail vehicles are also includes underground stations. Therefore the accidents discussed in this section also include accidents that have occurred in, e.g., subway stations.

In this section the following accidents are discussed:

- The fire at the King's Cross station, 1987
- The fire in the Hirschengraben tunnel in Zürich, 1991
- The fire in the Baku Metro, 1995
- The fire in Kaprun, 2000
- The Daegu subway fire, 2003
- The fire in Rinkeby, 2005

2.1.1. King's Cross, 1987

In November 18, 1987, a fire started in one of the escalators at the King's Cross station in London. The fire claimed the lives of 31 people, including one fire fighter, and injured several more (Donald & Canter, 1990; Fennell, 1988; Wildt-Persson, 1989). Although the fire did not occur in one of the trains, nor on any of the tracks, the disaster is still very interesting within the scope of this report due to the detailed investigations that have been performed afterwards. Especially a study by Donald and Canter (1990), in which the behaviour of the evacuees (both those who survived and those who died) has been analysed.

The King's Cross station was at the time of the disaster a complex station built in five levels where passengers were forced to move through a branched system of escalators, moving walkways, stairways and tunnels. It was through this system that people evacuated. No reports of people evacuating through the tunnels have been found. Five different tube lines trafficked the station and every weekday an average of 250 000 people used the station (Donald & Canter, 1990; Fennell, 1988; Wildt-Persson, 1989). The fire started in one of the escalators leading down to the Piccadilly line, ten meters below the main ticket hall, see Figure 1. An investigation of the fire showed that a lighted match is the most likely cause of the fire. It is believed that the match ignited a mixture of grease and detritus underneath the escalator (Fennell, 1988). The smoke produced in the escalator gradually moved up to the main ticket hall, which was later engulfed in flames (Donald & Canter, 1990; Fennell, 1988; Wildt-Persson, 1989).

The magnitude of the disaster can be linked to a combination of organizational factors failing. The first person to respond to the fire was a member of the staff. He went to inspect the fire after an alarm had been raised by one of the passengers. However, he was not based at the King's Cross station and had not received any fire training. Also, he informed neither the station manager nor the line controller. Furthermore, at the time of the disaster the London Underground did not have an evacuation plan to actualize (Fennell, 1988).

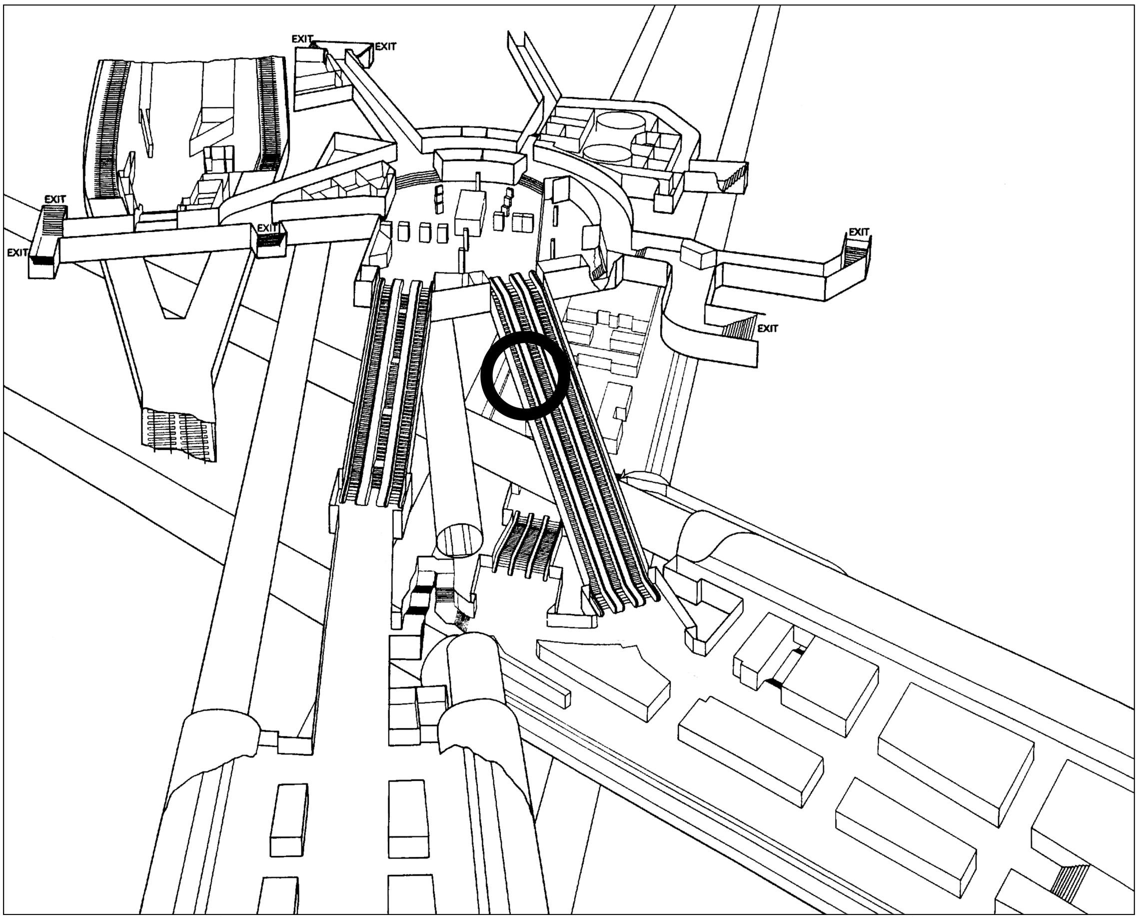

Figure 1. A picture of the King's Cross station with the Picadilly line to the lower right of the image. The circle marks the spot of the fire source (Fennell, 1988). By permission according to PSI License.

One of the most interesting of Donald and Canter's (1990) conclusions is that people at the King's Cross station maintained their roles during the fire. Passengers behaviour initially changed very little or not at all. Their actions were not modified until they received enough cues about the fire, very clear instructions from people who represented an authority or until evidence of the fire became so very obvious that a great change in their behaviour was necessary for survival. For instance, many passengers noticed smoke coming up from the escalator while entering the station but despite this continued to travel down to the tube lines (Donald & Canter, 1990).

Another interesting conclusion is the fact that people's responses to the underground instructions from staff were slow and sometimes nonexistent (Donald & Canter, 1990). In contrast, when the police started taking control of the evacuation people responded to a much bigger degree. Furthermore, Fennel (1988) reports that the public address system was not used during the fire to inform people of the evacuation. No information on whether a fire alarm bell was used or not has been found.

Donald and Canter (1990) have also observed the fact that staff lost valuable time due to unnecessary investigations of the fire. Investigations were first carried out by junior staff, who then called on senior staff who themselves investigated the fire and so on. Four different groups adopted this type of behaviour before taking on appropriate actions. The same type of investigating behaviour, not taking other peoples observations seriously, have been observed in other accidents as well, for instance in the Rinkeby subway fire (Statens Haverikommission, 2009).

During the fire in the King's Cross station, trains continued to run on the tracks underground, although the train drivers were instructed not to stop at the King's Cross station (Fennell, 1988). However, some trains did stop at the station and this resulted in people getting off. After the flashover of the main ticket hall trains still continued to stop at the King's Cross station, but now with the purpose to evacuate trapped people from the Victoria Line (Fennell, 1988).

The fire brigade arrived at the King's Cross station about 15 minutes after the first report of the fire. While they prepared themselves and their equipment for the rescue operation the main ticket hall was engulfed in flames, their main objective therefore changed from fighting the fire to helping evacuating passengers still coming out of the station. After more than two hours they reported having the fire under control and after further four hours the fire was extinguished (Fennell, 1988; Wildt-Persson, 1989).

2.1.2. Zürich, 1991

On the 16th of April 1991, a fire occurred on a train in the Zürich Metro. The fire, most likely caused by arson, was located in the end of the train. When the train was leaving the Zürich main station (for the Stadelhofen station) a station officer saw the fire and tried to get in contact with the train driver through headquarters but failed. A conductor who was travelling in the opposite direction also noticed the fire, and just like the station officer he tried to get in contact with the train driver through headquarters but without succeeding. The train driver was therefore unaware of the fire until a passenger pulled the emergency break inside the 1.2 kilometre long Hirschengraben tunnel. By pulling the break the train came to an immediate stop (Fermaud, Jenne, & Müller, 1995). Although the fire was not put out and despite the fact that the train stopped in the middle of the tunnel there were no recorded injuries or fatalities (Carvel & Marlair, 2005; Fermaud, et al., 1995).

When the train had come to a stop inside the tunnel, most of the passengers remained seated. They had not seen the fire, nor felt the smell of the smoke, so they stayed in their seats. The situation was not yet perceived as threatening (Fermaud, et al., 1995). The train driver tried to get in contact with the headquarters without succeeding; he therefore left the train to use one of the rail telephones. As more people discovered the fire, passengers started to move to the front of the train and in interviews afterwards they argued that they did so because this was the instructions they received from the train staff (Fermaud, et al., 1995).

When passengers started to move to the front of the train they received clear instructions from the train staff not to disembark. Despite the instructions, some passengers tried to get off the train but were held back by other passengers. A couple of minutes later new instructions were given to the passengers to start evacuating the train and head in the direction of the Stadelhofen station (Carvel & Marlair, 2005; Fermaud, et al., 1995). At this time the flames lashed out of the windows in the car subject to the fire, but there was still small amounts of smoke in the tunnel. However, it was only a couple of minutes later that the smoke density began to increase rapidly.

Soon after the first train subject to the fire had come to a stop in the tunnel, a second train coming from the Stadelhofen station also stopped in the tunnel due to a warning signal. The second train stopped in close range of the first train, see Figure 2. As the smoke started to fill the tunnel the train driver of the second train decided drive back to the Stadelhofen station, but after 100 meters he stopped to pick up evacuees from the first train. Due to a power outage the train could not continue back to the Stadelhofen station, and also the second train had to be evacuated. This meant that evacuees from the first train had to evacuate a second time. Just as in the first train, it was not until the train staff had given clear instructions that an evacuation was initiated. Fermaud et al. (1995) means that this demonstrates the importance of information and personnel-training for this kind of situations. Furthermore, they conclude that instructions or orders must be communicated with speed and competence.

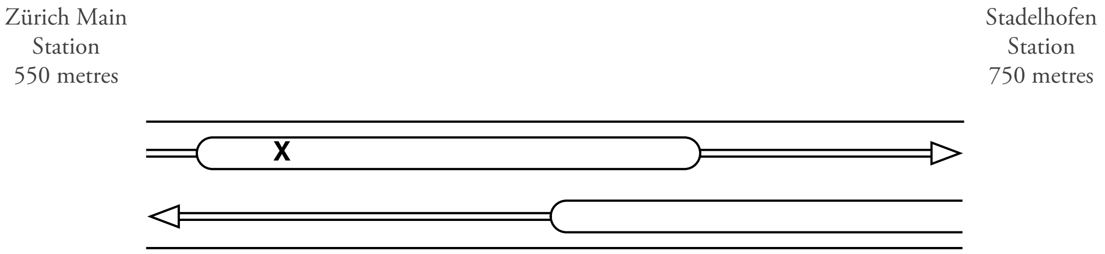

Figure 2. An illustration of the two train's position after they had come to a stop inside the Hirschengraben tunnel. X approximately marks the source of the fire and distances to the two closest stations are given. The arrows indicate in which direction the trains were travelling before coming to a halt. (Fermaud, et al., 1995).

When the passengers disembarked the train they had to overcome a vertical distance of 1 metre between the upper surface and the train. Despite this very few fell and in interviews conducted with the passengers they stated helping one another and that no one shoved. In the interviews more attention was given to the insufficient lighting. Not only was the lighting obscured by smoke, the train itself cast a shadow onto the evacuation route due to the position of the lights (Fermaud, et al., 1995).

The evacuation proceeded without any particular difficulties even though a large proportion of the passengers walked in smoke the whole time. Everybody walked towards the Stadelhofen station because this was the instruction they had received while still inside the train. Some people tried to walk between the rails but soon returned back to the walkway due to difficulties walking on the track. Interviews of the passengers conducted after the accident showed that very few of the questioned had noticed the handrail mounted in the tunnel wall. Instead people felt their way along the concrete wall or held each other's clothes or hands. Furthermore, pictograms on the walls were seldom noticed. In one case a pictogram even led to a misinterpretation. In contrast, information about distances to the Stadelhofen station inside the tunnel was perceived as very valuable. No information on how the ventilation was operated has been found. However, there are reports of a quick smoke filling of the tunnel due to a draft blowing in the travel direction (Fermaud, et al., 1995).

Fire fighters assisted the evacuating passengers in the tunnel as the passengers got close to the Stadelhofen station. They provided the passengers with information on how far it was to the portal and assisted the ones that were injured. In the interviews, the interviewed passengers said that there were some problems understanding the fire fighters due to the protective masks, but several mentioned that they were uncertain if they would have made it without the assistance (Fermaud, et al., 1995).

2.1.3. Baku, 1995

In October 28, 1995, an electrical failure led to a fire on one of the trains in Baku's Metro. The electrical failure caused a fire in the fourth of five cars and made the train to stop between two stations, Uldus and Narimanov, 200 meters after leaving the station Uldus, see Figure 3. The fire, still one of the worst to have occurred in an underground metro, killed 289 people and injured 265. (Rohlen & Wahlström, 1996).

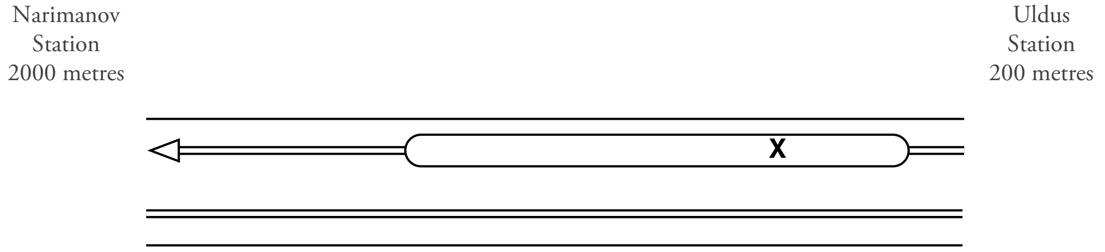

Figure 3. An illustrative picture of the train's position inside the tunnel after coming to a stop. The fire started in the fourth of five cars and X roughly marks the position of the fire. Distances to the closest stations are presented in the figure. However, as the fire grew the option to evacuate to Uldus diminished. The arrow indicates in which direction the train was travelling (Rohlen & Wahlström, 1996).

The human behaviour in the accident and what happened after the train came to a stop inside the tunnel has not been very well documented. Yet, some information can be found in the report by Rohlen and Wahlström (1996). Exactly what initiated the evacuation is unclear, but as the train came to a stop smoke soon began to fill the tunnel. The train driver noticed that there was something wrong, got out and used one of the tunnel telephones to contact the traffic information centre. Among other things, the driver instructed the operators to cut the electricity off since the cars were still supplied with electricity. (Rohlen & Wahlström, 1996)

At the same time passengers initiated the evacuation. Due to crowding, it is not likely that they observed the emergency door openers but since the electricity was shut off the emergency door openers would not have functioned anyway. The only way to open the doors was to slide them open with manual power, a complicated procedure when people are leaning against the doors. Instead windows were smashed to provide exits. Unfortunately, this enabled the smoke to travel into the cars. The train driver assisted the evacuation by opening the doors in the front and the end of the train, making it easier to travel from the back of the train to the front. The passengers that managed to exit the cars initially had the option either to evacuate back to Uldus (200 meters) or in the train's direction to Narimanov (2000 meters). But as the fire grew, the option to evacuate to Uldus diminished (Carvel & Marlair, 2005; Rohlen & Wahlström, 1996).

The evacuation was not only impeded by the toxic smoke, which made it hard to breathe, but also by the reduced lighting in the tunnel and by a trench that ran between the rails. The lighting consisted of unprotected light bulbs that were placed high and constantly lit. The smoke produced by the fire effectively covered these bulbs, thus reducing the visibility (Rohlen & Wahlström, 1996). The trench that ran between the rails made it difficult to walk at the tracks, which forced passengers to travel close to the tunnel wall, grasping cables along the wall. Passengers also held each other's clothes in order to not get lost in the dark tunnel (Rohlen & Wahlström, 1996). Initially the ventilation conditions tended to move the smoke slowly towards the rear of the train, towards Uldus. But around 15 minutes after the train had come to a stop the directional mode of the ventilation was changed and smoke began to move towards Narimanov, further impeding the conditions for the evacuees (Carvel & Marlair, 2005).

A majority of the deceased died inside the train without ever getting out. The fast fire growth played its role but most certainly the inability to open the train doors affected the outcome. It is hard to draw any conclusions about the organisational factors during the fire, but they seem to have been inadequate. For instance, the passengers evacuating to Narimanov did not receive any medical treatment when they arrived at the station because all the fire fighters were at Uldus. Furthermore, it seems as if the information from train staff to passengers were more or less nonexistent (Rohlen & Wahlström, 1996).

2.1.4. Kaprun, 2000

On the 11th of November 2000 a fire occurred in a funicular train in the town of Kaprun in Austria. The disaster claimed the lives of 155 people and only twelve of the passengers in the train cars survived. The fire started in a hot-air fan placed in the back of the train due to overheating and eventually spread to the rest of the train. Due to the fire the train halted 600 metres into the tunnel (Bergqvist, 2001; Larsson, 2004). Although the fire did not occur in a general underground tunnel it is discussed within the framework of this report because it involves the evacuation of people inside a tunnel.

The railway in Kaprun was used to transport skiers to the top of Kitzsteinhorn, a mountain in the county of Salzburg. In order to get to the top, a 30 metres long train had to travel 3.9 kilometres, going through an ascending tunnel that was 3.3 kilometres long with a 45° gradient (Larsson, 2004). Previous to the disaster experts considered the train to be incombustible. However, investigations that were carried out afterwards showed that an enhanced glass fibre material building up the train in combination with hydraulic oil fuelled the fire. It is also believed that passengers clothing and skiing equipment can have contributed to the fire load (Bergqvist, 2001; Larsson, 2004; National Geographic Channel, 2004).

Two trains occupied the track at the same time; one train ascending from the valley station and one train descending from the top station. The trains were tied together with a cable and were operated from the stations. Inside the tunnel there was a passage for the trains to pass one another. At this passage a 600 metres long emergency tunnel, running perpendicular from the main tunnel, was located. It was the train ascending from the valley station that eventually caught fire and came to a stop, see Figure 4 for the position inside the tunnel. There was no train driver onboard the trains, however, an attendant in the front of the train controlled the doors (Bergqvist, 2001; Larsson, 2004; National Geographic Channel, 2004).

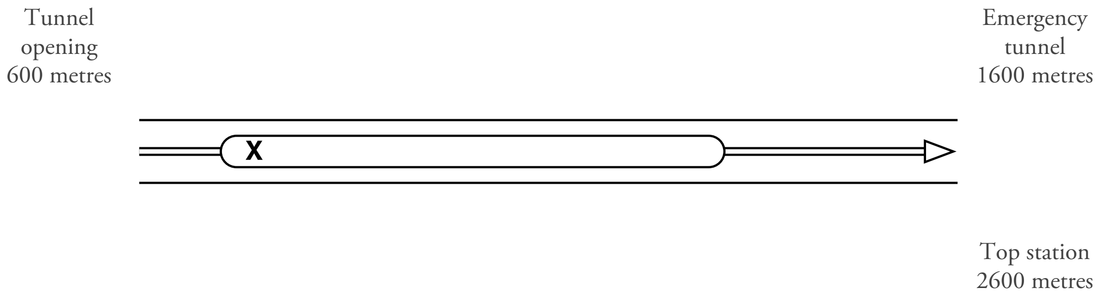

Figure 4. The train's position inside the tunnel. The fire started in the back of the train, in a hot-air fan, and the source of the fire is marked with X. Distances to the closest opening, emergency tunnel and station are given. The arrow indicates that the train was ascending towards the top station (Larsson, 2004).

The first observation of the fire was made by one of the passengers inside the train who could smell smoke just before the train entered the tunnel. As the train continued to ascend inside the tunnel, more and more people noticed the fire. One person tried to call the emergency service centre but failed because he had no cell phone signal. The passengers had no possibility to contact the train attendant because there was no communication system inside the train. Furthermore, acrylic glass, used to separate the train cars from each other, made it impossible for passengers in the back to walk up to the train attendant. As the train came to a stop inside the tunnel passengers soon tried to open the doors but failed. The doors could not be opened manually from the inside, nor from the outside, but had to be opened by the train attendant. Instead some of the passengers tried to break the windows with their skis, skiing boots or other possessions (Bergqvist, 2001; Larsson, 2004).

Three minutes after the train had come to a stop inside the tunnel, the train attendant managed to get in contact with the control room and informed them of the fire. He was immediately ordered to open the doors to let the passengers out. Shortly after this the communication link between the control room and the train was terminated (Bergqvist, 2001; Larsson, 2004).

When the passengers had disembarked the train they had two choices. Either they could travel downward, passing the fire, to the valley station or up towards the top station. As the fire was spreading rapidly inside the tunnel the temperature was rising fast. Smoke was produced due to the fire and started to fill the tunnel as well as ascend to the top station. A situation much like the one in a chimney was created because of the gradient of the tunnel. Many of the passengers that escaped the train instinctively evacuated up towards the top station but they did not have a chance against the fire and the smoke. Most people died only 10-15 metres from the train, some were found 50 metres from the train and only one person was found 150 metres up in the tunnel. The few that survived, twelve people, were the ones that choose to travel down towards the valley station. Apart from the extreme heat and the toxic smoke the evacuation was impeded by the narrow escape route; a 0.7 metres wide stairway designed for tunnel workers that were very steep. Furthermore, the skiing outfit had a negative impact on the evacuation. For instance, some of the passengers were wearing skiing boots, which made them stumble on their way down (Larsson, 2004).

Inside the sister train, coming from the top, two people were travelling: a passenger and the train attendant. This train had also stopped in the tunnel due to a cable connecting to the other train. It was not long until the smoke reached them and they had no chance of surviving. The smoke continued to the top station where it started to fill the building. Five workers managed to escape the station before it was filled with toxic smoke (Larsson, 2004).

Seven minutes after the trains had come to a stop inside the tunnel the fire brigade in Kaprun was informed about the fire. After additionally five minutes the fire brigade in Zell am See, close to Kaprun, was alarmed. The fire fighters that arrived at the valley station concentrated on helping the evacuating passengers coming from inside the tunnel. Due to the extreme heat and the smoke a rescue operation inside the tunnel was impossible. Three fire fighters from Zell am See arrived at the top station and immediately initiated the search for survivors inside the station. They found four people, three of which were already dead. After a couple of hours the fire had extinguished on it's own and the work with evacuating the dead was initiated (Larsson, 2004).

The magnitude of the disaster can be linked to a combination of shortcomings. The inability for the passengers to make contact with the train driver, as well as the absence of emergency door openers played a great role. But the lack of technical installations also had an impact on the outcome. For instance, there were no emergency signs inside the tunnels to direct the evacuating passengers, and no instructions were given to passengers (Larsson, 2004). The trains were provided with some fire appliances, however, these were located in the train attendant's cabins and were thus not available for the travelling passengers (Larsson, 2004). Also, the fact that no one had considered a fire inside the tunnel is likely to have contributed to the disastrous outcome.

2.1.5. Daegu, 2003

On the 18th of October 2003 an arsonist set fire to a train that had stopped at the Jungangno Station of the Daegu Metropolitan subway in South Korea. The arsonist used two milk packages filled with a flammable liquid to set the train on fire, and it was not long until the whole train was engulfed in flames. The fire spread in the insulation between the layers of aluminium that form the shell of the cars, in the vinyl and plastic material in the seat cushions and in the plastic matting on the floors, none of which were flame retardant. The fire killed at least 189 people and injured around 150 people (Carvel & Marlair, 2005; Kirk, 2003).

Along with the arsonist, many of the passengers in the train on fire managed to escape. However, a second train was allowed to stop at the station close to the origin of the fire although the operator was aware of the fire. Shortly after the train's arrival, an automatic fire detector detected the fire and turned off the electricity preventing the second train to leave the station. This train eventually caught fire, explaining the many victims. Without the electricity the doors could not be opened with the emergency openers, which effectively trapped the passengers (BBC News, 2003; Carvel & Marlair, 2005).

The magnitude of the disaster was later linked to a combination of faulty emergency signals, poor communications and misjudgements by subway staff who had received little or no training on how to cope with the situation (DePalma, 2003). After the disaster a nationwide revision was made of the South Korean subway stations with regard to fire safety. It was found that 149 of 556 stations had smoke control problems and 99 stations did not have acceptable evacuation routes (The Japan Times, 2003).

2.1.6. Rinkeby, 2005

On the 16th of May 2005 a fire occurred in the undercarriage of a train car at the subway station in Rinkeby, Sweden. The fire is believed to have started because of electrical arcs created by an electrical discharge. No people were killed in the accident, however, 12 people suffered from smaller injuries (Statens Haverikommission, 2009).

A passenger who observed the fire ran forward to inform the train driver when the train had come to a stop at the Rinkeby station. The train driver initially told the passenger not to worry, but as he could see sparks from the rear of the train he was convinced that something was wrong. After leaving the driver's cabin the train driver went to examine the sparks for himself and noted smoke coming from under the train. He then ran back to the cabin and informed the passengers to evacuate the train where after he contacted the traffic control centre (Statens Haverikommission, 2009).

The traffic control centre ordered a ticket seller at the Rinkeby station to help the train driver evacuate the station. A traffic commander was also directed to the Rinkeby station to get a picture of the situation (Statens Haverikommission, 2009). There was no automatic fire alarm, nor any sprinklers, to detect or suppress the fire. A passenger at the Rinkeby station calling from a cell phone was the first person to present information about the fire to the emergency service. At about the same time a call was received from the traffic control centre (Statens Haverikommission, 2009).

Most of the passengers on the train could evacuate the station without any problems and before the conditions became untenable. However, the train driver and four passengers were trapped inside the station due to the fire and had to cross the tracks to get to another platform where conditions were better. At the other platform they met up with the traffic commander. They decided to evacuate up via an escalator but halfway up the traffic commander, the train driver and a male passenger turned around due to thick smoke. The other three passengers continued up and managed to escape to the outside by travelling through the smoke. The persons that were stuck on the platform decided to evacuate via the tracks to the Rissne station after consulting with the traffic control centre (Statens Haverikommission, 2009). Movies recorded from the accident shows that the tunnel was free from smoke and that the lighting was turned on, providing the evacuating persons with a good visibility.

There seems to have been communication problems during the fire. The train driver tried to reach the traffic control centre several times without success. He wanted them to turn on the lighting in the tunnel towards the Tensta station and for them to shut turn the electricity off to make it possible to walk on the tracks (Statens Haverikommission, 2009).

Some time after the accident The Swedish Accident Investigation Board conducted interviews with passengers that had been on the train or on the station when the fire erupted. Based on these interviews it doesn't seem as if the train driver or the operator had a clear strategy for how to cope with the evacuation. Much of their behaviour seems to have been improvised to fit the situation. Another interesting conclusion that can be drawn from the interviews is that several of the interviewed persons cannot recall having heard an emergency message from the loudspeakers (Statens Haverikommission, 2009).

According to the investigation by the Swedish Accident Investigation Board the magnitude of the situation wasn't initially fully understood. They mean that if an evacuation is to be performed effectively the traffic controller needs to receive information about the situation to be able to perform the tasks assigned to him adequately. In the fire at the Rinkeby Station the traffic controller lacked a checklist to follow which might have led to tasks being performed in an erroneous order or that they were forgotten (Statens Haverikommission, 2009).

2.2. Accidents in underground transportation systems for road vehicles

Because there are many similarities in an evacuation from underground transportation systems, both for road and rail vehicles, valuable information can be gathered from past accidents in road tunnels as well as from underground rail facilities. Therefore three fires that have occurred in road tunnels are discussed in this section:

- The Mont Blanc tunnel fire, 1999
- The Tauern tunnel fire, 1999
- The Burnley tunnel fire, 2007

2.2.1. Mont Blanc, 1999

On the 24th of March 1999 a truck loaded with flour and margarine caught fire about halfway through the 11.5 kilometre tunnel in Mont Blanc, close to vehicle rest area 21, see Figure 5. The fire, which started in the truck cab, fast developed to a massive fire that took fire fighters more than two days to extinguish. It claimed the lives of 39 people and the material damages on the tunnel were severe (Duffé & Marec, 1999; Voeltzel, 2002; von Hall, 2000).

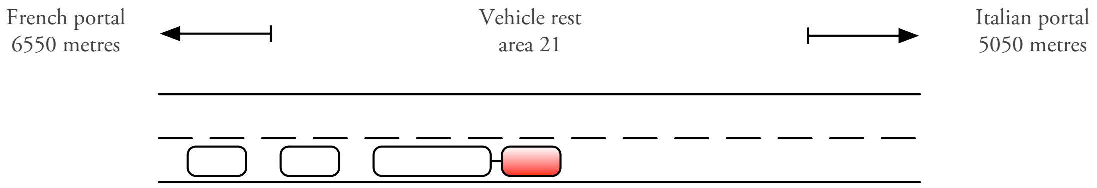

Figure 5. An illustrative picture of the vehicle's position inside the tunnel. Distances to the closest portals are given, approximately measured from the fire. The red cab indicates where the fire started. From the HGV the distance to the closest safety shelter was approximately 300 metres in either direction (Duffé & Marec, 1999; Voeltzel, 2002).

After the accident much of the criticism was aimed at the organisational factors. The tunnel was operated in a cooperation between a French and a Italian company meaning there were two control centres (each responsible for half of the tunnel), but after the accident it appeared the cooperation was more or less nonexistent with the companies operating only in their own half of the tunnel. This lack of cooperation and organisation is believed to have further worsened the consequences of the accident (Duffé & Marec, 1999; Voeltzel, 2002; von Hall, 2000). In case of a fire it was expected of the staff in the control centres to activate the ventilation system. The fact that there were two control centres in the Mont Blanc Tunnel complicated the situation further. During the fire the Italian operators did not follow procedures and kept the ventilation in supply mode. Thus, when the French operators activated the emergency ventilation there was an increase of the air velocity towards the French portal. This evidently accelerated the smoke propagation towards the French portal and effectively impeded the conditions for the evacuees (Voeltzel, 2002).

Every hundred meters safety niches could be found equipped with two fire extinguishers and a fire alarm push button. However, the investigation by Duffé and Marec (1999) concludes that no attempt was made to extinguish the fire. Emergency telephones were located every 150 meters and was used during the accident by different people (Duffé & Marec, 1999). Apart from the safety niches the tunnel was equipped with vehicle rest areas every 300 metres, numbered 1-36 from the French portal. Every other vehicle rest are was equipped with a refugee area (safety shelter). The refuge areas were supplied with fresh air and were designed to protect people from a fire for at least two hours. In their investigation Duffé and Marec (1999) concludes that these shelters saved the lives of many people who tried to evacuate the tunnel. However, the shelters seem to have been somewhat hard to find for some people.

In the fire 27 of the victims never left their cars. According to the investigation most of these victims probably did not see the fire before it started to spread to other vehicles (Duffé & Marec, 1999). In addition, two persons took refuge in an other vehicle and nine died outside their vehicle (Voeltzel, 2002; von Hall, 2000). Two persons sought shelter in safety shelter 20 but were deceased as the fire burned for over 50 hours (Duffé & Marec, 1999). Those who did leave their cars and survived had to travel in an untenable environment due to smoke and obscuration of the lighting. It was not until 20 minutes after the beginning of the fire that the tunnel operators gave a radio message to the tunnel users informing about the fire (Voeltzel, 2002).

2.2.2. Tauern, 1999

In May 29, 1999, a collision between a heavy goods vehicle (HGV) carrying paint canisters and several other vehicles led to a fire in the Tauern Tunnel. The tunnel is 6.4 kilometres long and the accident occurred about one kilometre from one of the openings in the vicinity of a construction site, see Figure 6. The fire claimed 12 persons lives, 22 cars and 12 trucks were burnt out and parts of the tunnel carved in as a result of the fire (Bergqvist, 2000; Voeltzel, 2002).

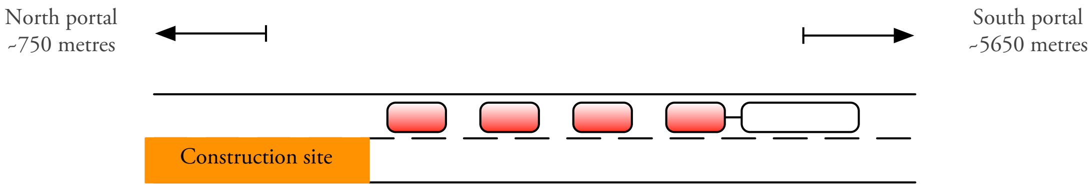

Figure 6. An illustrative picture of the vehicle's position inside the tunnel. Distances to the closest portals are given, approximately measured from the fire. The red cars and HGV indicates where the fire started after the collision (Voeltzel, 2002).

In contrast to the Mont Blanc tunnel fire only two of the deceased persons stayed in their cars. Another victim also perished when he, after he had started to evacuate, returned to fetch documents in his car. Eight persons were killed in the initial accident. Emergency call niches were placed every 212th metre and were equipped with a fire alarm push button, a telephone and two fire extinguishers. The emergency phones were used by some of the evacuating drivers but no one attempted to extinguish the fire using the fire extinguishers (Voeltzel, 2002).

In the Tauern tunnel fire, three evacuating persons took shelter in one of the emergency niches. In fact, the Tauern tunnel didn't have any safety shelters. Voeltzel (2002) argues that perhaps they thought that they were in a safe area, but also states that an emergency niche shouldn't be able to mistake for a safety shelter. Due to the smoke, the people were trapped in the emergency niche and had to be rescued by firemen by modifying the ventilation conditions to clear up the smoke (Voeltzel, 2002).

In comparison with the Mont Blanc Tunnel fire, there was only one control centre in the Tauern Tunnel. Further, the source of the fire was immediately located and the ventilation system was of higher performance. Also, actions taken by the operators seem to have been taken rather fast, e.g., it only took three minutes after the fire start to close the tunnel to traffic (Voeltzel, 2002). However, no information to initiate an evacuation was played in the loud speakers inside the tunnel (Bergqvist, 2000).

2.2.3. Burnley, 2007

On the 23rd of March 2007, a traffic accident involving both trucks and cars triggered a fire in the Burnley Tunnel in Australia. The tunnel, which is 3.4 kilometres long, runs under the Yarra River in Melbourne, Australia, and was at the time of the fire used by around 100 000 vehicles per day, of which 14 000 were trucks. It consists of three lanes and traffic is only allowed to travel in one direction. In the accident, three people were killed, all of whom were involved in the initial accident (Dix, 2010; Johnson & Barber, 2007).

The accident occurred around 1.4 kilometres into the tunnel, just at the end of a downhill grade. Due to a tyre blow-out a truck was forced to stop in the left lane[1]. This was recognized by the CCTV system and around two minutes later the tunnel operator closed the left lane and also reduced the allowed speed limit inside by changing computer controlled signs. However, a second truck did not acknowledge the halted truck and initiated a collision including five cars and three trucks. The collision was followed by a number of explosions and according to Dix (2010) a fire generating 10s of megawatts was instantaneously initiated. The cars ahead of the accident were able to drive out of the tunnel. However, approximately 200 cars and 400 people had to leave their cars and evacuate (Dix, 2010; Johnson & Barber, 2007).

Around thirty seconds after the collision the tunnel operator initiated an emergency response, which among other things meant that the tunnel was closed. Ninety seconds after the collision at least two radio messages had been broadcasted to the tunnel users, the smoke extraction system had been activated, as well as the fixed fire suppression system. The people who had to leave their cars either walked back to the tunnel entrance or used cross passages and exit stairs leading to the Domain Tunnel, a tunnel parallel to the Burnley tunnel. None of these evacuees were injured and their vehicles also survived the fire (Dix, 2010; Johnson & Barber, 2007).

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[1] Australia has left-hand traffic

A combination of a fast response from the tunnel operator and the effectiveness of the fixed fire suppression system and the ventilation system seem to have contributed to the few deaths and injuries. Furthermore, the damages on the tunnel were so small that it could re-open the next day. It seems as if the drivers took the radio broadcasted messages seriously, because they initiated an evacuation fast enough. Johnson and Barber (2007) argued that the success of the emergency management system was due to a combination of pre-planning, fire drills and other training.

2.3. Summary

The accidents discussed in this chapter are summarized with regard to number of fatalities and injuries, the cause of the accident, the source and type of information given to passengers and on what type of surface the evacuation was performed in Table 1.

Table 1. A summary of the accidents discussed in this chapter. The outcome describes the deaths/injuries in that accident (- means that no information has been found).

	Year	**Cause of the accident**	**Outcome**	**Information to passengers**	**Evacuation**
King's Cross	1987	Grease and detritus ignited by a match in one of the escalators at the King's Cross station.	31/-	Instructions from police and underground staff on the platforms to evacuate. Cues from the fire.	Essentially through stations, travelling on platforms, escalators and staircases. Also by trains. Many people evacuated in smoke.
Zürich	1991	Most likely an arsonist setting one of the trains on fire. Because of the fire the train came to a halt inside the Hirschengraben tunnel.	0/0	Instructions from train staff to start evacuating and in which direction. Cues from the fire.	Initially passengers had to overcome a one meter height difference, thereafter the evacuation proceeded inside the Hirschengraben tunnel along the tracks. The evacuation was performed in smoke.
Baku	1995	An electrical failure causing a fire on one of the trains. Due to the fire the train came to a halt inside the tunnel between stations Uldus and Narimanov.	289/265	Evacuation seems to have been initiated by cues from the fire, rather than by instructions from staff or other technical installations.	Initially through windows due to an inability to open the train doors. Thereafter inside the smoke filled tunnel.
Kaprun	2000	Overheating in an electrical fan causing a fire. Due to the fire the train came to a halt inside the tunnel.	155/-	Evacuation seems to have been initiated by cues from the fire, rather than by instructions from the staff or other technical installations.	Initially through windows but after a couple of minutes through the train doors. Outside the train evacuation proceeded inside the sloping tunnel with a 45° inclination on a 0.7 metre narrow staircase. Evacuation was performed in smoke and heat.
Daegu	2003	An arsonist starting a fire in a train situated at the station.	189/150	Evacuation seems to have been initiated by cues from the fire, rather than by instructions from the staff or other technical installations.	Essentially through the Daegu station. Most likely in thick smoke.
Rinkeby	2005	An electrical failure causing a fire in the undercarriage of a train situated at the Rinkeby station.	0/12	Instructions from train driver to initiate evacuation. Cues from the fire.	Essentially through the Rinkeby station, to some extent smoke logged. Three persons evacuated through a tunnel to another station.
Mont Blanc	1999	A fire starting in a truck cab inside the tunnel	39/-	Radio message after 20 minutes. Cues from the fire.	Essentially inside the smoke filled tunnel.
Tauern	1999	A collision between a HGV and several other vehicles	12/-	Cues from the fire.	Essentially inside the smoke filled tunnel.
Burnley	2007	A collision including three trucks and five cars.	3/0	Computer controlled signs changing, radio broadcasted message. Cues from the fire.	Essentially inside a smoke free tunnel due to a fast operator response and technical systems of good performance.

There is a great variation in the accidents discussed above, as well as in the outcome of the accidents. Much of the information in this chapter has been acquired from investigation reports and it is not always that the human behaviour and the evacuation is well described since these investigation reports tend to focus more on the technical aspects and the reason for the accident. In the following, a collection and discussion about the most important observations and conclusions is given.

Accidents involving a great number of dead or injured people and major material damages can seldom be explained by one single critical event leading up to the severe consequences. Instead, these types of accidents are more often explained by a chain of critical events that together cause the damage. However, in order to avoid deaths in a fire it is required that the available safe escape time is longer than the required safe escape time. It is clear that an evacuation was not initiated in time for a safe evacuation in many of the accidents that have been discussed above.

One of the reasons as to why evacuation sometimes is delayed is given by Donald and Canter (1990) who argues that people maintain their roles, even in the event of an emergency. Furthermore, each role is associated with a set of behaviour rules, i.e., guiding principles that will influence the actions taken in a fire situation. This role keeping behaviour is demonstrated by the human behaviour in the King's Cross fire. Some people saw the fire but did not think it was their job to deal with it because of their passenger role. Others simply did not receive enough fire cues to abandon their objective as a passenger. The same type of role keeping behaviour was also identified in the fire in the Zürich Metro where people remained seated until they received instructions from the train staff to either move to the front of the train or to disembark it (Fermaud, et al., 1995). The fact that passengers will not leave the train in which they are travelling have also been demonstrated in experiments conducted in the Eurotunnel. In the experiments cosmetic smoke was produced in the front wagon of a train. Although people saw the smoke they remained seated. Some closed their windows to keep the smoke out of their own car and it was not until they received instructions to leave the train or saw others leaving as they initiated the evacuation (Donald & Canter, 1990).

This suggests that evacuation is not regarded as a proper behaviour to a person who has adopted the role as a passenger. Neither is extinguishing fires. Thus, when a passenger receives ambiguous information about a fire, or instructions to initiate an evacuation, this information is easily neglected. It is important to bear this in mind when trying to understand human behaviour in fire. If not, it is likely that a perfectly rational behaviour is interpreted as irrational when viewed from an observer's perspective, e.g., an accident investigator.

However, there are measures to be taken in order to initiate an evacuation. One of these is linked to the information that passengers receive about a situation. In both the King's Cross fire and the fire in the Zürich Metro it was observed that passengers responded fast when given instructions on what was the matter and what to do (Donald & Canter, 1990; Fermaud, et al., 1995). This type of fast response was also observed in the Burnley Tunnel fire were a radio broadcasted message was carried out by the tunnel operator (Dix, 2010; Johnson & Barber, 2007). Thus, the recognition of a single cue might not always be enough for a passenger to respond to an emergency. However, when provided with much information, e.g., fire cues in combination clear and coherent information and instructions, a passenger is more likely to change his or her objective and begin evacuation.

However, if the information is to help people and to shorten the evacuation time it should come fast and it should be clear. At best it should come from the operator or an authority, e.g., the police (in the fire at the King's Cross station it was observed that people did not respond very well to train staff (Donald & Canter, 1990)). In turn this would demand a good organisational structure, a clear strategy on how to act in the event of an emergency and that involved staff is well educated.

The lack of a good organisational structure as well as educated members of the staff can be highlighted by some actions (or inactions) in the accidents discussed in this chapter. For instance, in the fire at the King's Cross station the members of the staff investigated the fire unnecessarily long. They seem to have lacked a reporting chain and no evacuation plan existed (Donald & Canter, 1990; Fennell, 1988). In the fire in Kaprun, no routines for how an evacuation should proceed existed simply because fire was not thought of as a potential scenario and no information or instructions were given to the passengers (Bergqvist, 2001; Larsson, 2004). In Rinkeby, the same investigating behaviour as identified at the King's Cross station was adopted when the train driver did not believe a reporting passenger. Furthermore, the staff seems to have lacked adequate training for an emergency situation (Statens Haverikommission, 2009). In Mont Blanc the consequences have been linked to a bad organisation and a lack of routines (Voeltzel, 2002). Thus, if occupants underground are to be provided with proper information so that they can initiate an evacuation as fast as possible in the event of an emergency it is clear that there needs to be an organisation for this and that members of the staff are well trained. In contrast to the above accidents, the positive effects of a well trained staff (in combination with good technical solutions, e.g., a ventilation system and a fixed fire suppression system) can be illustrated by the Burnley tunnel fire in which no other than the people involved in the traffic accident were injured (Dix, 2010; Johnson & Barber, 2007).

So far this discussion have mainly paid attention to the time before an evacuee starts to evacuate, i.e., the response time, which has been demonstrated to be strongly related to roles and information. However, the outcome of the accidents discussed above can also be linked to technical installations (or the lack of them). The organisational factors played a big role in the outcome of the King's Cross fire. In contrast, it was essentially the technical systems that failed in the fires in both Baku and Daegu where emergency doors could not be opened with the emergency openers due to power outage (BBC News, 2003; Carvel & Marlair, 2005; Rohlen & Wahlström, 1996).

A technical installation that has been demonstrated to very much affect the efficiency of an evacuation is the lighting conditions. This is unique in underground facilities where no natural light is provided and where the surface is not always is even. Most often the lighting is placed in the ceiling, which makes it vulnerable to smoke from the fire (it is easily obscured). When the visibility is impaired the movement speed is reduced, as have been seen in many of the accidents discussed above, e.g., the fire in the Zürich Metro, in the Baku Metro and in the Mont Blanc tunnel (Duffé & Marec, 1999; Fermaud, et al., 1995; Voeltzel, 2002; von Hall, 2000). In some of the accidents, e.g., in the Baku Metro and the Zürich Metro, passengers even adopted a behaviour where they held on to each other, each other's clothes or felt their way along the concrete wall not to get lost in the darkness (Fermaud, et al., 1995; Rohlen & Wahlström, 1996). The Zürich Metro was provided with handrails, however, they do not seem to have been used by the evacuees because they were not seen.

In Zürich the passengers had to overcome a one meter vertical height difference when they disembarked the train (Fermaud, et al., 1995). According to the interviews with passengers afterwards this was not considered a big problem. However, it can be concluded that this would probably not have been the case if people with some kind of disability had been on the train, e.g., a movement disabled person.

Technical solutions to guide evacuees in case of an emergency are emergency exit signs and signs giving information about distances. The literature does not discuss these solutions very much, but information from the fire in the Zürich Metro argues that emergency signs did the direct opposite than to guide people. One evacuee argued that he was mislead by a emergency exit sign (Fermaud, et al., 1995). However, signs that provided information on distances to the stations were appreciated by the evacuees.

It may seem that if only one of the evacuees complained about a misleading emergency exit sign it was not experienced as a big problem. However, emergency exit signs must be designed and placed so that the risk of misinterpretation is minimized. Furthermore, emergency exit signs are often placed high which means that smoke is likely to obscure them in a fire. A solution could be to combine signs that are placed high with signs that are placed low.

Smoke from a fire does not only impair the vision and obscure way-finding signs. It also contains toxic products from the fire that evacuees are exposed to when evacuating in a smoke filled environment. A good ventilation system that is being operated according with emergency instructions in case of a fire is therefore of great importance if conditions are to be improved for the evacuees. In both the Tauern fire and the Burnley Tunnel fire, a ventilation system of high performance and a fast response by the operators might have contributed to the relatively few deaths (Bergqvist, 2000; Dix, 2010; Johnson & Barber, 2007). In contrast, a poor ventilation system in combination with ignorance worsened the conditions for evacuating people in the Mont Blanc fire and the fire in the Baku Metro (Carvel & Marlair, 2005; Voeltzel, 2002). But again, as have been mentioned above, in order for emergency ventilation systems to function as intended it requires that the operator knows how to operate it. In turn, this demands training.

2.3.1. Lessons learned

The most important observations from the fires discussed in this chapter, in terms of fire evacuation in underground transportation systems, are presented below:

- People tend to maintain their roles, and the associated rules to the roles, even in fire emergencies.
- Fast and clear information can help shorten the total evacuation time.
- The response from occupants in underground transportation systems seems to be better when an authority, e.g., the police, provides the information.
- Lighting is very important in underground transportation systems and has a positive effect on the movement speed. Lack of lighting can lead to an affiliative behaviour.
- Signs providing information on distances to the closest exits is appreciated in fire emergencies.

3. Theories in human behaviour

To understand human behaviour in fire, theories and models have been developed during the last forty years. These theories and models are valuable when trying to understand and describe the human behaviour in fires in underground transportation systems. The development have gone from treating building users as nonthinking objects and often blaming the outcome of an accident on 'panic' towards a more sophisticated view on the processes linked to human behaviour (Sime, 1995). In the following sections these theories and models for understanding human behaviour in fire are presented. The link to fire evacuation in underground transportation systems is not clearly pointed out, as these theories and models constitute the foundation for understanding human behaviour in fire and evacuation in general.

3.1. The egress time-line model

In the event of a fire, occupants should be able to evacuate before conditions become untenable. In the field of fire safety engineering a comparison is therefore often made between the *available safe escape time* (ASET) and the *required safe escape time* (RSET). The ASET is the calculated time available between the ignition of a fire and the time at which tenability criterions are exceeded. The RSET is the calculated time between the ignition of a fire and the time when all occupants have completed the evacuation. In order to reach an acceptable margin of safety the RSET should be shorter than the ASET (Proulx, 2008). Initially the RSET was based only on the estimated time it took people to move to the closest exit. No account was taken to the fact that peoples initial responses to a fire can take significant time before an evacuation is initiated (Sime & Kimura, 1988).

Today the egress time-line model have been developed and the RSET is no longer made up only by the movement time, but it is divided into a recognition time, a response time and a movement time, see Figure 7.

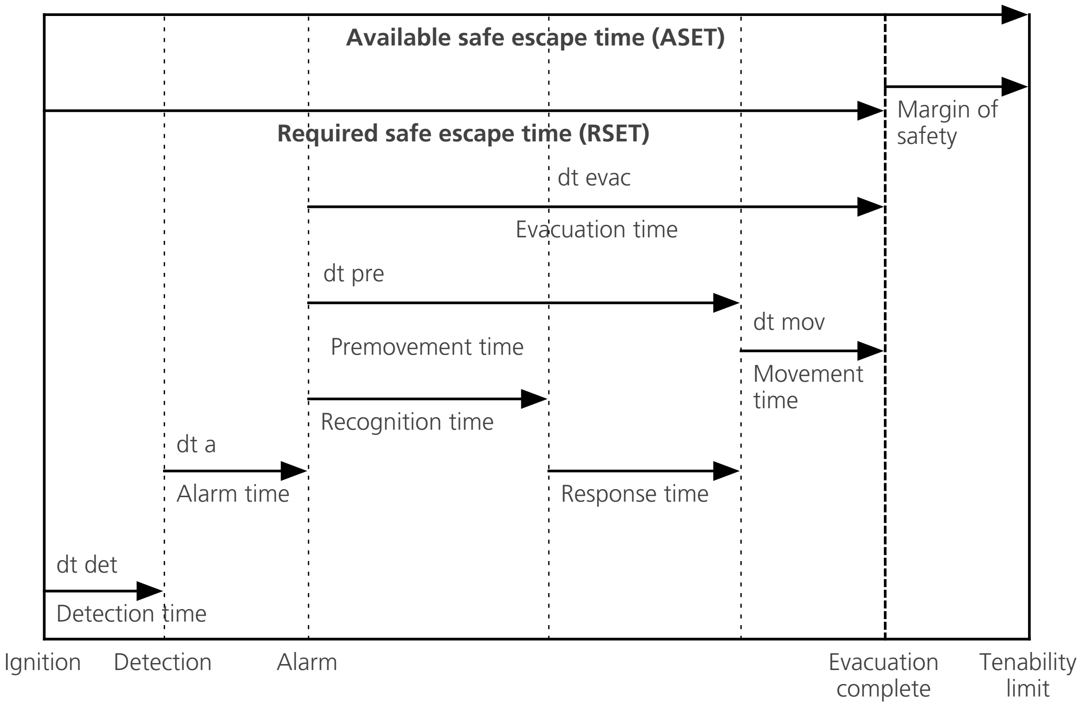

Figure 7. The egress time-line model (Proulx, 2008).

Often the ASET is determined by calculating the time between the fire start and the time when untenable conditions are reached, e.g. the time until a certain temperature in the smoke layer is reached. However, an alternative and more complex approach have been developed where the dose of a toxicant in the body is regarded. By comparing the accumulated dose received (the product of concentration and time) and the effective dose to cause irritation/incapacitation/death, the *fractional effective dose* (FED) is calculated. With this approach consideration is taken to the actual distance that a person is travelling inside a building where he or she is exposed to toxicants (Purser, 2008). To calculate the FED the following equation can be used:

FED = Dose received at time t (Ct) / Effective Ct dose to cause irritation/incapacitation/death

3.2. Behaviour sequences

With the purpose to understand human behaviour in fire Canter et al. (1980) performed detailed studies of human behaviour in fires (domestic, multiple occupancy and hospital fires). Among other things, it was investigated how people became aware of the fire and how they acted after being aware of it. Information was gathered from fire brigades along with interviews conducted with survivors (Canter, et al., 1980). The investigations resulted in the behaviour sequence model and can be used to describe human behaviour in fire, see Figure 8.

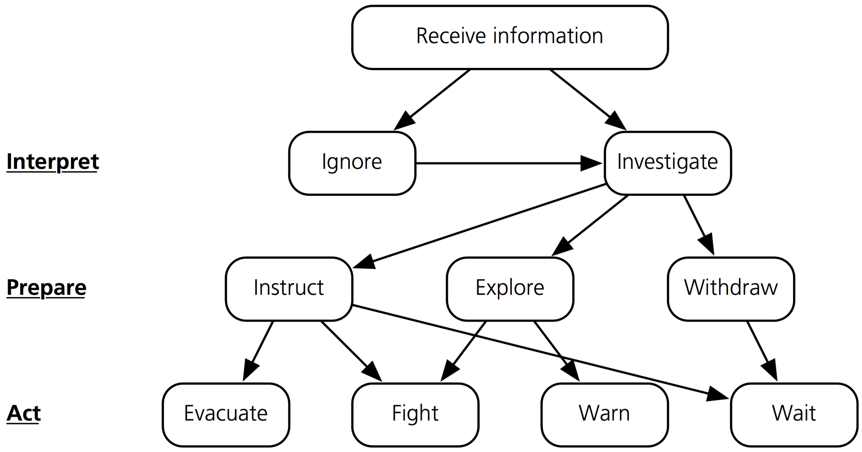

Figure 8. The behaviour sequence model (Canter, et al., 1980).

Figure 8 demonstrates that human behaviour in fire can be described by three sequence categories, or so called nodal points: interpret, prepare and act. Furthermore, each nodal point constitutes a behaviour sequence, i.e., a sequence of consecutive actions that people perform. The figure also demonstrates that as the sequence of behaviour unfold, the potential actions increase in variety. Canter et al. (1980) do not claim that all behaviour in fire are efficient, effective or intelligent. However, by adopting the model seen in Figure 8, human behaviour in fire can be described without the use of the word ‘panic’, which today is a questioned explanation of human behaviour in fire (Sime, 1980).

In the early stages of a fire, information and fire cues are scarce. Consequently, the decisions that a person makes early in the early stages of a fire are associated with great uncertainties. However, as people receive more information about the fire the uncertainty associated to the decision-making is reduced. According to the behaviour sequence model, the initial phase of evacuation is characterised by uncertainty and information gathering. When a person receives an initial cue he or she can either ignore it or begin to look for additional information, i.e., investigate. This interpretation stage is common to all evacuation processes and can often contribute significantly to the total evacuation time.

Behaviour sequences, i.e., how a specific person responds to a fire, have been shown to depend highly on the role of the person, e.g., if the he or she is a member of staff or a passenger. Each role is associated with a set of behaviour rules. The rules can be seen as guiding principles associated to the role that a person has adopted, and they will influence the actions taken in a fire situation (Canter, et al., 1980; Tong & Canter, 1985). Thus, a person who has adopted a passenger role will not respond in the same way as a member of staff. The study by Canter et al. (1980) has also shown that the relative roles of non-fire situations, e.g., passenger versus staff, will affect behaviour in fire situations. For example, if a station manager is a figure of authority during normal operation the same trend can also be expected in case of fire.

3.3. The affiliative model

Early on Sime (Sime, 1985a, 1995) argued that an integration of psychology and engineering was needed in order to consider the actual users of a building. He suggested that a building should not be designed in an attempt to control the building's users, but rather to accommodate the user's social, psychological and cultural needs. In his PhD thesis he presented the affiliative model to aid the understanding of human behaviour in fires (Sime, 1984). The model dismisses the physical science model, which assumes that people always choose the shortest evacuation route, i.e., the closest exit, when evacuating. Instead, the affiliative model assumes that people in an emergency are more likely to be drawn to places or persons that are familiar to them (Sime, 1983, 1985b). This often means that people choose to evacuate the same way they came in when they entered the building because it is familiar, and also that the evacuation often takes place within groups to which the person has previous ties. Consequently, it is argued that people avoid unfamiliar escape routes because they are unfamiliar.

In a study with the objective to demonstrate the model, Sime (1985b) analyzed the Marquee Showbar fire, a fire on the Isle of Man, United Kingdom, that claimed the lives of 50 people. The analysis was performed by going through the approximately 500 police interviews that had been conducted with the survivors after the fire. Sime (1985b) concluded that the most important factors that influenced the direction of movement and choice of exit in the fire was a combination of:

1. A person's role, e.g., staff member or visitor, and their familiarity with escape routes
2. A person's ties to individuals in other parts of the building, e.g., family members, friends
3. The proximity of emergency exit doors

For instance it was concluded that the staff, regularly using the fire exit as a personal entrance and thus familiar with it, used this exit more consistently than the public who were not familiar with it.

3.4. Social influence

In addition to the behaviour sequence model and the affiliative model, the presence of others, i.e., social influence, have been shown to affect a person's decision to evacuate (Latané & Darley, 1968). Furthermore, a distinction can be made between normative and informational social influence.

Latané and Darley (1968) have developed a sequence model, similar to the one developed by Canter et al. (1980). They argue that a person goes through a process of four steps if he or she is to intervene in an emergency:

1. The individual has to notice the event
2. The individual has to define the situation as an emergency
3. The individual has to decide that he or she is responsible for taking action
4. The individual has to choose a particular course of action to take

Furthermore, they argue that there are a number of variables influencing the likelihood of a person acting or not. Their hypothesis is that the most critical of those variables are the presence of others, i.e., social influence (Latané & Darley, 1968).

In order to test this hypothesis Latané and Darley (1968) performed an experiment with male students in Colombia University, USA. In the experiment the test subjects were told that they were participating in a large-scale study about problems of urban life. The subjects were called to an interview, but prior to the interview they were placed in a waiting room where they were instructed to fill out a form. However, after a couple of minutes smoke was introduced to the room through a small vent in the wall. After four minutes enough smoke had filtered into the room to obscure vision, produce a mildly acrid odour and interfere with breathing (Latané & Darley, 1968).

Three different versions of the experiment were performed to test the hypothesis. In the first scenario only one test subject was present in the room. In the second scenario three persons were present, none of whom where informed about the real purpose of the experiment. In the third scenario three persons were present, however, two of whom where passive participants who knew what was going to happen. The passive participants were instructed to look up when the smoke was introduced, then return to the form and if addressed with a question only answer "I dunno" (Latané & Darley, 1968). The results from the experiment are presented in Table 2.

Table 2. Results from the experiments conducted by Latané and Darley (1968). "Times action were taken" refers to the number of experiments where the subject left the room due to the smoke(Latané & Darley, 1968).

	Number of experiments	Times action were taken	Proportion
Scenario 1	24	18	75 %
Scenario 2	8	3	38 %
Scenario 3	10	1	10 %

From the experiments it can be concluded that when the subjects were alone in the room they reacted to the smoke more often than if in the room with others, thus accepting the hypothesis presented above. The biggest difference was achieved in the comparison of the first and the third scenario. In the third scenario it was likely that the test subject was influenced by the passivity of the others (Latané & Darley, 1968).

Another interesting observation is related to how fast the smoke was observed. By comparing the first scenario with the second and the third it was observed that the subjects were noticing the smoke much faster when they were alone. Within five seconds 63 % of the subjects had noticed the smoke in scenario 1, in comparison with scenario 2 and 3 where only 26 % of the subjects noticed the smoke within five seconds. Latané and Darley's (1968) explanation to this is the fact that people kept their eyes fixed on the forms to avoid appearing rudely inquisitive in scenario 2 and 3. Nilsson (2006) argues that these results suggest that it can take longer for people to react to early fire cues when other people are also present.

Latané and Darley's (1968) experiment thus demonstrated that the presence of others is likely to impinge on a impinge on a person's decision to evacuation. Furthermore, a distinction can be made between normative and informational social influence (Deutsch & Gerard, 1955).

Normative social influence is defined as an influence to conform with the positive expectations of another (Deutsch & Gerard, 1955). By positive expectations Deutsch and Gerard (1955) refer to those expectations that leads to a positive feeling when fulfilled by another. They mean that people are afraid of standing out or to make fools of themselves and therefore their individual judgements often conform to other people's expectations. This type of social influence have been confirmed in experiments carried out by Deutsch and Gerard (1955).

Informational social influence is defined as an influence to accept information obtained from another as evidence about reality (Deutsch & Gerard, 1955). This means that people look at other people's behaviour who are in a similar (or the same) situation when deciding what action to take, i.e., people copy other people when uncertain on how to behave. By performing experiments Deutsch and Gerard (1955) could show that the more uncertain a person was about the correctness of his or her individual judgement, the more sensitive he or she was to social influence when making individual judgements.

Research has also been carried out to study the link between social influence and ambiguous information. Solomon et al. (1978) conducted experiments to examine people's reactions to an emergency and compared people's reactions when they were alone to when they were a part of a group. Both laboratory experiments and field experiments were carried out and the main issue was to examine the willingness to help an injured person who simulated fainting. In general, the experiments showed that the more ambiguous information about the emergency, the less likely bystanders were to act. However, a difference could also be seen between individual and group reactions, independent of the number of cues received about the emergency. When people were alone they were more likely to respond to the emergency. Although the experiments did not focus on a fire situation, they highlight the fact that social influence is important when an emergency situation provides ambiguous cues.

Nilsson and Johansson (2009) further discusses this problem. In experiments they investigate social influence during evacuation experiments from a cinema theatre. By comparing the visitor's response to an alarm bell and a pre-recorded message respectively they found that social influence was more important when the information from the fire was limited (when the alarm bell was used). Furthermore, they discovered that social influence increased with decreased distance between people.

3.5. The theory of affordances

The theory of affordances was first introduced by Gibson (1977) and was further explored a couple of years later in Gibson (1979). Gibson developed this theory to explain how people perceive the things they see and meant that human perception can be explained as the interaction between the human (or more generally speaking: the organism) and the surrounding environment. According to this theory the perception of an object is linked to what it offer or afford to the organism in relation to it's goal (Gibson, 1979). For instance, a stairway consists of adjacent steps. It is however not perceived as a number of adjacent steps, but rather as an object for travelling up or down because it offers it's user the possibility to both ascend and descend.

Affordances linked to an object would, if they were measured, be able to explain in standard physical units. For instance, the stairway mentioned above could be measured in terms of gradient or number of steps. However, to the organism these properties are measured relative to the organism. In other words (Gibson, 1979):

> *They are unique for that organism and not just abstract physical properties.*

This means that a full-grown person perceives the stairway in one way and a crawling infant in another, simply because the stairway does not afford the possibility to ascend or descend to the infant.

Hartson (2003) expanded Gibson's original theory of affordances and argued that the affordances provided by an object can be divided into different categories depending on the type of aid the object gives the user. The categories are presented in Table 3 with short explanations.

Table 3. A development of Gibson's (1979) theory of affordances (Hartson, 2003).

Category	**Explanation**
Sensory affordance	A design feature that helps the user in sensing the object (e.g., seeing, hearing or feeling).
Cognitive affordance	A design feature that helps the user to understand what the object is used for.
Physical affordance	A design feature that helps the user in doing something.
Functional affordance	A design feature that helps the user to achieve his/her goal.

The theory of affordances has been used in various fields of research. For instance, it has been implemented in the human-computer interaction design (Hartson, 2003). In the field of fire safety engineering the theory has been used to explain human behaviour in fire, for instance why certain designs of emergency exits perform poorly in the event of an evacuation (Sixsmith, Sixsmith, & Canter, 1988). These experiments are discussed in detail below. Because the theory of affordances is intertwined with the design of an object it is useful when trying to understand and interpret present research regarding fire technical solutions, e.g., emergency exit signs.

In the 1980s Sixsmith et al. (1988) performed experiments in a large shopping mall in northern England with the purpose to study if doors faced with murals had any impact on how they were used in an evacuation. In the study 50 participants were asked to imagine that an alarm had sounded and that they should find and use the nearest exit door. By studying and plotting human behaviour, escape routes and the time from start to finish the authors were able to draw conclusions regarding the effectiveness of the doors by adopting the theory of affordances (Sixsmith, et al., 1988).

It was observed that most people managed to exit the centre, although not always by the quickest or most effective route. Many people failed to see and identify nearby exits and continued to walk straight past visible exit signs. Twenty-eight percent of the participants used the nearest door while 22% used the second nearest. Furthermore, 24 % of the participants adopted strategies directly inappropriate to an evacuation in the event of a fire (Sixsmith, et al., 1988).

Sixsmith et al. (1988) meant that during the experiment it became clear that the participants were confused by the mural faced doors. The doors were simply not recognized as emergency exit doors. In interviews performed after the experiment the participant's reactions were overall negative. They meant that the doors were hidden, confusing and some argued that the doors was perceived as a part of the wall.

The mural faced doors were consequently not appreciated by the participants and Sixsmith et al. (1988) identified two problems related to this type of doors. First of all they were not recognized as emergency exits. Furthermore, the inability to recognize emergency exits could lead to confusion in the event of a fire. By using the theory of affordances it is possible to, at least to a certain degree, try to explain why there is a problem with mural faced doors.

First of all, the mural faced doors did not have door-like affordances. By melting in with the rest of the wall they sent the message of closedness, not openness. They were perceived as solid barriers to people not knowing beforehand that they were doors. Sometimes the perception of the doors were so strong that even the emergency sign above the door was insufficient in inviting the participants to use that door (Sixsmith, et al., 1988). However, it could be argued that the passageway inside the large mall also provided affordances to the occupants. If a passageway is perceived as a path leading somewhere, for instance to an exit, it is possible that this contributed to the inappropriate use of the exiting doors.

In his dissertation, Nilsson (2009) have examined and experimented on different technical solutions that could provide occupants with affordances suitable in the event of an evacuation. Some of these results are summarized in chapter 1 but not in terms of affordances.

3.6. 'Panic'

The term 'panic' has often been used to explain the human behaviour in disasters such as fires, as well as the outcome of these. It has been suggested that 'panic' can occur even if there is no direct danger. Furthermore, Nilsson (2009) has interpreted old building legislations and writes that 'panic' has been thought of something that could spread among a group of people like a highly infectious decease. Although there is no solid definition to the term, it has been used as a comfortable way of describing a complex series of events (Rogsch, Schreckenberg, Tribble, Klingsch, & Kretz, 2008). Sime (1980) argues that a reason for this could be that the use of the term can be used as an explanation to the outcome of an accident without demanding any further investigation of the accident itself.

In 1980 Sime (1980) argued that the term 'panic' was being overused by different groups (e.g., firemen, journalists and the public) with different backgrounds and involvement in fire. It was being used as a description, explanation or evaluation of human behaviour. Often media used it to explain the magnitude of a disaster, and in turn this affected the people but also the building legislations. Sime (1980) meant that one reason for this overuse of 'panic' linked to crowd flight could be because attention then was being directed away from the individual's perspective. Thus, it was a comfortable way of describing a complex process but also to put the blame on someone/something else. However, the use of 'panic' as an explanation to human behaviour replaced a more systematic approach to the subject (Sime, 1980).

In 2008 Rogsch et al. (2008) presented a study of 127 incidents that led to a mass evacuation. The purpose was to quantify the number of accidents were 'panic' could be used to explain the human behaviour. In the beginning of their article 16 different definitions of the term 'panic' was introduced, highlighting the problems with using the term to explain certain types of human behaviour. By creating their own definition based on these definitions an investigation was made of the 127 incidents. They concluded that the term 'panic' could be used to explain the human behaviour in two of the 127 incidents, thus suggesting that 'panic' does not occur as often as suggested in the literature. The definition of 'panic' used by the authors was (Rogsch, et al., 2008):

> *People flight based on a sudden subjective or "infected" fear. People are moving imprudently. The cause of this movement can not be recognized by an outsider.*

Similar conclusions have also been made in other studies, in which the same type of investigations has been carried out. (Fahy, Proulx, & Aiman, 2009).

4. Empirical research

Empirical research in short means research that is based on data collection from observations in experiments. In order to study a certain problem or a certain design experiments are sometimes carried out to examine the effects. The empirical research with a connection to human behaviour, evacuation and technical systems are discussed in the following sections.

A series of studies have been identified within the frameworks of this reports. These studies are briefly described as an introduction, thereafter the results are read upon in the following sections. The presentation of the results will follow a chronological emergency model where a presentation of factors relating to the premovement time is followed by a presentation of factors relating to the movement time (flow of people from trains, travel speed and choice of exits), see Figure 7.

4.1. Information about the experiments

In this section the studies and experiments that have been carried out are presented. Very briefly the purpose of each experiment is given as well as information about the experiment itself. Relevant information related to test participants is given in most cases. Note that the results are not summarized in this section, they can be found in section 4.2-4.5.

4.1.1. Experiments on walking speed in fire smoke

Jin (1976) performed experiments in a smoke filled environment with the purpose to examine at what distance a fire exit sign could be distinguished. At the same time the movement speed was measured. The experiments were carried out in a 20-meter long corridor filled with smoke and test subjects were instructed to start at the end of the corridor and walk towards the exit. The movement speed was measured in each experiment by letting the subjects hold a wire connected to a big reel. A total of 10 subjects participated and were all male. Experiments were carried out both with and without lighting. (Jin, 1976)

4.1.2. Experiments on human behaviour in fire smoke

In order to examine the human behaviour in a smoke filled environment, Jin (1981) performed tests in a chamber without windows but with illumination at floor level with 30 lx on average. Test subjects were seated at a table one at a time. On the table a metal plate with four holes was placed and the subjects was instructed to fit a metal stylus into the holes without touching the edges. As they did this, irritant smoke was introduced into the room and the smoke density was gradually increasing. After the test the subjects were instructed to walk to the end of the room, to push a button and then to walk back. The distance was about 10 metres and was travelled in the smoke. By taking notes of the steadiness test, as well as the subjects heart rate, respiratory rates and walking speed, Jin (1981) attempted to draw conclusions related to the emotional instability due to smoke from fires (Jin, 1981).

The human behaviour in smoke filled environments has also been studied by Heskestad (1999) who re-analysed five Norwegian experiments on human behaviour in smoke. The main purpose was to evaluate and to quantify especially two parameters: the movement speed and the probability of making a correct decision when moving through an evacuation route. The original experiments included over 300 participants, who generally were unfamiliar with the layout of the tests. In all the tests the participants moved through a constructed path of way guidance systems and most often in environments with fictional smoke where the visibility was less than three metres (Heskestad, 1999).

4.1.3. Experiments on exit signs

Jin, Yamada, Kaway and Takahashi (1991) carried out an experimental study consisting of two experiments to determine the conspicuousness of different types of exit signs. In the first experiment a regularly used exit sign at the time was examined and in the second experiment a flashing sign was compared to the traditional sign. In both experiments the same 33 test subjects, both male and female without defects of vision, was instructed to walk towards a sign and while walking evaluate the conspicuousness of the sign at different distances. The conspicuousness was indicated on a scale from 1-5 based on how they were perceived.

McClintock, Shields, Reinhardt-Rutland and Leslie (2001) have also examined the conspicuousness of emergency exit signs. In order to examine whether or not traditional emergency exit signs (with a white running man on a green background) were perceived by occupants in a building, a study was carried out in three steps. In the first step it was examined if people in general associated the emergency exit signs with safety or not. In the second step it was examined if the exit signs were noticed during everyday conditions. In the third and final step it was investigated if a technical solution added to an emergency exit sign could improve it's ability to capture occupants attention. The study was performed by interviewing people, often members of the public outside a retail store. In the first part of the study, 90 people participated. In the second part, 500 people participated and in the third part 361 people participated (McClintock, et al., 2001).

4.1.4. Experiments on informative fire warning systems

An informative fire warning system (IFW system) is a sophisticated fire alarm which is able to provide the occupants in a building with not only a warning about the fire, but also information about the location of the fire, it's size and it's spread. The reason for an IFW system is mainly to reduce the delay in commencing an evacuation (Bellamy & Geyer, 1990). The Building Research Establishment has examined the effect of IFW systems and the results are presented in two reports (Bellamy & Geyer, 1990; Canter, Powell, & Booker, 1988).

Canter, Powell and Booker (1988) thoroughly investigated the use of IFW systems and it's contribution to efficient evacuation by performing five studies, i.e. case studies of fire drills and examinations of the recall and comprehension of IFW messages. The fire drills were carried out in a geriatric ward of a general hospital, three smaller care establishments and two office blocks (Canter, et al., 1988). To be able to evaluate the human behaviour the drills they were video recorded. The study of people's ability to recall and comprehend IFW messages was examined in different experiments. Among other things the authors examined the effects of degree of message specificity, the effects of abbreviations and coded messages and the relevance of different types of information. The study was carried out by letting the participants watch computer generated graphic screens and then to note or decode their interpretation of the messages (Canter, et al., 1988). IFW systems could mean displaying on a computer screen the exact position of a fire, however, in the studies carried out by Canter et al. (1988) only text messages were used.

In the report by Bellamy and Geyer (1990) the effectiveness of display message components of IFW systems was evaluated. The study included a comparison between computer generated colour visual displays (3D, 2D and text), a comparison between computer generated audible signals (speech) and visual signals and an evaluation of the specific content of the messages. The evaluation included two experiments carried out in a laboratory with both male and female subjects who were instructed to make active actions when presented to different fire alarm situations. In the first experiment single mode presentations of IFW messages was carried out and compared, i.e., a comparison was made between different modes of IFW messages. In the second experiment multi mode combinations of IFW messages was tested based on the results from the first experiment, i.e., a comparison was made between different combinations of IFW messages (Bellamy & Geyer, 1990).

4.1.5. Evacuation experiments in the Newcastle Metro

Proulx and Sime (1991) performed emergency evacuation experiments in the most complex underground station in the Newcastle Metro with the objective to determine the effectiveness of different communication systems. The study was divided into two parts. First the day-to-day functioning of the station was examined and then the evacuation experiments were conducted. The type of information to the metro users were varied five times, see Table 4.

Table 4, the type of information given to users in each experiment (Proulx & Sime, 1991).

Experiment	Type of information
1	Alarm bell only
2	Alarm bell with two staff members
3	Alarm bell and minimal non-directive public announcements
4	Alarm bell with two staff members and directive public announcements
5	Alarm bell with improved directive public announcements

Because of similarities between the station were the experiments were conducted and the King's Cross station (which has been discussed in this report) a fire scenario much like the one in King's Cross was adopted. During the experiments the time to start to move, the time to clear the station and the objective appropriateness of the behaviour was measured (Proulx & Sime, 1991).

4.1.6. Evacuation experiments in the Stockholm Metro

Frantzich (2000) performed a study in the Stockholm Metro with the purpose to examine passenger's ability to move inside a tunnel in the event of a fire. In two evacuation experiments it was assumed that a train had come to a stop inside the tunnel due to a fire, and it was expected from the participants that they should evacuate the train, choose the appropriate travel direction and proceed to a safe location. Variations of the experiments were achieved by changing the lighting conditions inside the tunnel, ranging from total darkness to ordinary lighting. 143 volunteers took part in both the experiments and had been told beforehand that they were going to participate in an experiment regarding evacuation (Frantzich, 2000).

4.1.7. Evacuation experiments in the Benelux tunnel

Norén and Winér (2003) analyzed a series of experiments carried out in the Benelux tunnel in Rotterdam in the Netherlands by Boer and Veldhuijzen van Zanten (2005). The purpose was to determine the time spent in the different phases from the moment that an accident occurs in a road tunnel until it is fully evacuated, i.e., to quantify the total time needed for evacuation. In the tests a Heavy Goods Vehicle (HGV) followed by cars in both driving lanes entered a one-way tunnel with two driving lanes. When reaching the middle of the tunnel smoke started to develop from the HGV and shortly thereafter the HGV came to a halt, effectively blocking both lanes. Five minutes after the stop a message was played in the loudspeakers saying:

> *Attention, attention, there is an explosion hazard; I repeat, there is an explosion hazard*

After additionally two minutes the drivers were instructed to evacuate the tunnel. The participating drivers were not aware that they were going to participate in an evacuation experiment, however, they had been told that they were going to participate in an experiment to study driving behaviour. A total of nine tests were carried out with 40-50 cars in each test (Norén & Winér, 2003).

Norén and Winér (2003) also collected data on train evacuation with the same purpose as in the Benelux tunnel. To collect the data the authors studied the flow of people when leaving trains under normal conditions. Furthermore, they performed two planned evacuation emergencies where the participants knew the purpose of the study beforehand (Norén & Winér, 2003).

4.1.8. Evacuation experiments from a smoke filled rail carriage

Oswald, Lebeda, Schneider and Kirchberger (2005) carried out two full-scale experiments from a rail carriage with the purpose to investigate evacuation in smoke. Special attention was paid to the influence of raised floor levels and a raised passage inside the trains. In the experiments participants were partially subjected to smoke. The participants were briefed beforehand that they were going to participate in an evacuation experiment involving non-toxic smoke. The conclusions drawn from the experiments are mainly based on surveys that the participants filled out after the experiment (Oswald, et al., 2005).

4.1.9. Evacuation experiments from a high floor metro train

Oswald, Kirchberger and Lebeda (2008) carried out two experiments with the purpose of studying the passenger flow through a metro train's exits. In the experiments it was assumed that a train had come to a stop due to an incident, e.g., a collision, and it was expected from the participants that they should evacuate the train. The first experiment was carried out in the free on the tracks, while the other experiment was carried out in a simulated tunnel. In the experiments more than 440 people of different age and gender participated. Attention was especially aimed at two factors: the close geometry for passage between the metro cars and the tunnel wall and the vertical height between the train and the surface.

4.1.10. Evacuation experiments from an overturned rail carriage

Galea and Gwynne (2000) performed two experiments in an overturned rail carriage with the purpose to estimate the flow rate capacity at the end exits. It was assumed that a rail carriage had turned over and was lying on the side when the evacuation was initiated. Around 30 people participated in each of the tests (the same participants in both) and were briefed beforehand that they were going to participate in an experiment about evacuation. In one of the experiments the participants were subjected to non-toxic smoke. Both experiments were carried out outside during daytime and with no emergency lighting. To minimize the risks for the participants a series of arrangements were made prior to the experiments, e.g., a levelling of the area just outside the doors to cover the rail tracks were performed.

4.1.11. Experiments on exit choice influencing

In Nilsson's (2009) dissertation the use of flashing lights at emergency exits and their effect on evacuating people have been examined. A thorough research including laboratory experiments, hypothetical scenario experiments and field experiments was carried out in order to develop recommendations about the design of emergency exit. The research and the results are principally based on the results from four papers.

In the first paper by Frantzich and Nilsson (2004) the walking speed and the human behaviour in a smoke filled tunnel were investigated. Experiments were conducted in a laboratory with test subjects walking through a 37 metre long tunnel, which was filled with irritant smoke. Three types of wayguidance systems were evaluated in the experiments: flashing lights, rows of flashing lights and floor markings. The test participants, both male and female in the ages of 18-29 years, were given limited information about the experiment beforehand. They were only told that they were going to walk in a smoke filled tunnel. Just before they entered the tunnel they were told that they had driven into a smoke filled tunnel and that they had came to a stop. It was expected of them to act as they would have done in a real situation. After the experiment the subject was asked to fill out a questionnaire about the experiment (Frantzich & Nilsson, 2004).

In the second paper both laboratory experiments and hypothetical experiments were carried out. The purpose of the laboratory experiments was to examine how well coloured flashing lights and strobe lights could influence people's choice of exit in a corridor. In the hypothetical scenario experiment a comparison between different colours was made to determine which colour was the most appropriate in the design of exit signs. A total of 172 test subjects participated in the study. In the laboratory experiments they were blindfolded, led into the corridor and then told to imagine that there was a fire inside the building. They were then instructed to find a way out. In the hypothetical study the test subjects were placed in front of a display of flashing coloured lights and strobe lights. Associating the lights to an emergency exit sign the test subjects were then asked to grade the different combinations (Nilsson, Frantzich, & Saunders, 2005).

The third paper constituting Nilsson's (2009) dissertation describes a field experiment carried out in Göta tunnel in Gothenburg, Sweden. The purpose was to evaluate the human behaviour of motorists inside a tunnel, and to determine how wayfinding systems were perceived. The test participants (27 male and 2 female) were told beforehand that they were going to participate in a study about driving behaviour. However, when they had driven into the tunnel they soon reached a simulated accident involving four cars and smoke. The test participants were asked to fill out two questionnaires, one prior to the experiment and one afterwards. The questions were related to the participant's emotional state, wayfinding systems, safety equipment and fire alarm (Nilsson, Johansson, & Frantzich, 2009).

In the fourth and final paper of Nilsson's (2009) dissertation, field experiments were conducted in order to investigate whether or not green flashing lights at emergency exits could influence the exit choice of evacuees. Experiments were performed both in an office building and in a cinema theatre and were performed as unannounced evacuations (Nilsson, Frantzich, & Saunders, 2008).

4.2. Results related to the premovement time

In studies it have been demonstrated that there are a number of factors that can influence the premovement time. For instance, lack of information about an emergency situation could prolong the premovement time, as well as social influence. These, and other factors that might influence the premovement time are discussed here. In Figure 7 it was suggested that the premovement time could be divided into a recognition time and a response time. However, they are not treated respectively in this section.

Canter et al. (1988) examined the role IFW systems in an evacuation because there are some problems with the traditional fire alarms, for instance: (1) people fail to differentiate them from other types of alarms, (2) people fail to regard fire alarms as authentic warnings of a genuine fire and (3) the alarm systems fail to provide people with information that could assist them in attempts to deal with the fire (Canter, et al., 1988). The main conclusion from the study is that IFW systems could play a big difference in the shortening of the overall evacuation time by dealing with the problems mentioned above. Estimations done by the Canter et al. (1988) suggest that up to two minutes could be saved by using an IFW system instead of a traditional fire alarm in large complex buildings. Recommendations on message length, use of abbreviations and message specificity, formulation and format were also given based on the observations from the studies. For instance, it was recommended that messages preferably should contain three units of information, that abbreviations should be avoided and that the exact position of the fire doesn't have to be described if it conflicts with the recommendation on message length. An important observation is also the fact that regardless how effective an IFW system is, it cannot reduce the evacuation time if the fire safety organisation is ineffective (Canter, et al., 1988).

Bellamy and Geyer (1990) also performed experiments on IFW systems. A general conclusion from the experiments was that a graphic 3D screen and a computer generated speech appeared to be the best types of IFW systems, performing better than text messages. When used, the highest proportions of immediate evacuation and genuine fire interpretation were achieved. Also, the shortest interpretation time and action decision times was observed. It was obvious that an IFW system was superior to the traditional fire alarm. Furthermore, observations from the second experiment suggested that a combination of IFW systems could reduce the total evacuation time additionally. However, when too many systems were combined the total evacuation time again increased. Thus, a combination of IFW systems was advocated but the combination should not include too many systems since there appears to be a risk of information overload. Generally a combination of a 3D picture and speech performed best in the experiments (Bellamy & Geyer, 1990).

That a traditional fire alarm, such as an alarm bell, is poor in terms of initiating an evacuation is also demonstrated by the experiments conducted by Proulx and Sime (1991). In the experiments it was observed that the underground users noticed the alarm bell, however, it was often discarded and people seemed to think that it had nothing to do with them. In contrast, the type of information systems used in experiment 4 and 5 (see Table 4) was most effective in terms of getting people to start evacuating. From this Proulx and Sime (1991) concluded the most important factors for a successful evacuation is:

- To give users prompt instructions
- To explain to the users what is happening, i.e., the reason for the alarm
- To explain to the users what to do and why, i.e. which emergency exit to choose

The lack of information and it's effects on the premovement time is illustrated by Frantzich's (2000) experiments conducted in the Stockholm Metro. In the first experiment, no message to inform the passengers about the situation (when the train had come to a stop inside the tunnel) was given. Due to this, it took the passengers almost nine minutes to initiate an evacuation from the train even though some passengers observed and smelled smoke after five minutes. In surveys filled out by participants afterwards, many argued that there was very little information for them to make a decision about whether to evacuate or not. From this Frantzich (2000) concludes that because passengers travelling underground does not have especially many sources of information, information from e.g., a train driver can play a big difference in decreasing the premovement time.

A comparison can be made to the second experiment where a message from the train driver was played to the passengers three minutes after the stop. This message immediately initiated the evacuation (Frantzich, 2000).

Results related to the same topic are presented in the report by Norén and Winér (2003) who conducted experiments in the Benelux tunnel. Among other things, the time it took people to abandon their vehicle due to the simulated fire was measured. Norén and Winér's (2003) observations showed that the population (consisting of participants) could be divided into two groups: those who left their car prior to the announcement about the explosion hazard (18%) and those who left their car after the announcement (82%). This is illustrated in Figure 9. Furthermore they concluded that (Norén & Winér, 2003):

> *the presence of other people affects the individual and results in group behaviour*

They also concluded that:

> *… one motorist opening a car door results in other motorists opening their doors too"*

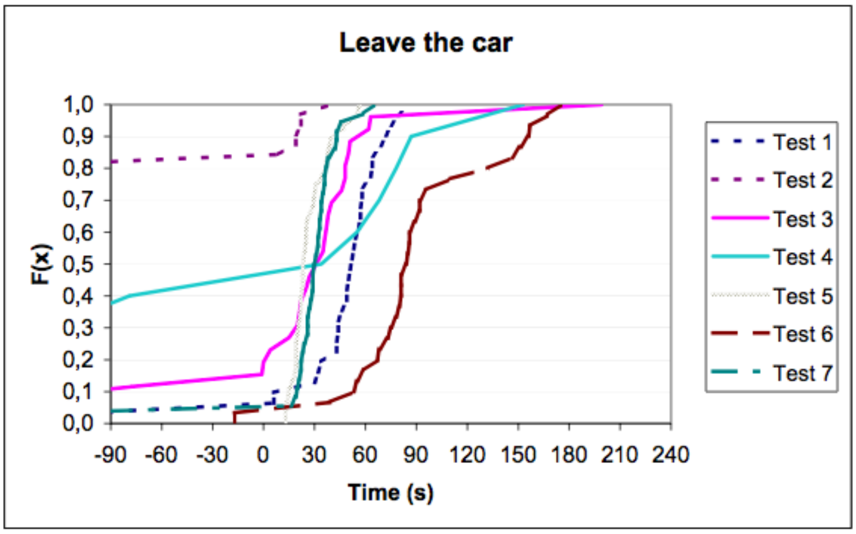

Figure 9. Cumulative frequencies of people leaving their car. The announcement was made at t = 0 seconds. By permission (Norén & Winér, 2003).

Between the two groups a difference in hesitation time could be identified. Norén and Winér (2003) define the hesitation time as the time between opening the door and the moment the driver begins walking away from the car towards an exit. It was observed that the group abandoning their cars prior to the announcement hesitated much longer than those who left their cars after the announcement. Norén and Winér (2003) argue that this is due to an effect of better information. Drivers who had received more cues about the emergency lost less time in the hesitation-phase. Furthermore, the proportion of the participants that did not hesitate at all and initiated an evacuation directly after the announcement was greater in the "after"-group. Norén and Winér (2003) conclude that the above observations highlight the need to make an announcement about an emergency as soon as possible.

In the road tunnel experiment described by Nilsson et al. (2009), quite the opposite observations were observed. In the experiments the premovement time was very short. All of the test subjects had begun to open the door to their car within 35 seconds after the car had come to a stop. The authors try to explain this fast response with an increased alertness among the participants due to the experiment, although the information was scarce, and an increased willingness to leave their cars because they probably knew it was a drill. Another explanation given by the authors is social influence. By seeing other people before you initiating an evacuation it seems easier to make a decision to leave your car. Because the premovement time was relatively short only ten passengers were still in their cars when a pre-recorded alarm started to sound. Therefore it is hard to draw any conclusions regarding the alarm, however, those still in their cars mentioned that it was somehow unclear and that it was hard to hear what was said. Despite this, the participants argued that they perceived the alarm as positive since it made them respond to the accident, to look for more information and to initiate the evacuation (Nilsson, et al., 2009).

4.3. Results related to the passenger movement

The passenger flow through a train exit is dependent on a number of factors. Among other things the proportions of the people exiting the train, the vertical height between the train and the surface and lighting conditions influence the flow. Passenger flows have been measured in various studies and are discussed in this section. In Table 5 quantified observations are summarized.

Frantzich (2000) measured the passenger flow in the experiments carried out in the Stockholm Metro, see Table 5. The train used in the experiments was equipped with emergency exit ladders, and during the evacuation these were used at some of the exits to overcome the vertical distance between the train and the surface, see Figure 10. Although they provided support for some people, Frantzich (2000) observed a couple of problems related to the emergency ladders. For instance, the passenger flow was decreased at those exits where the emergency ladders were used. Furthermore, it took a considerable time to mount the ladder and during this time very few people could use the exit to disembark the train without the ladder. It was also observed that people stood and waited for their turn, even though other available and open exits were not used (Frantzich, 2000).

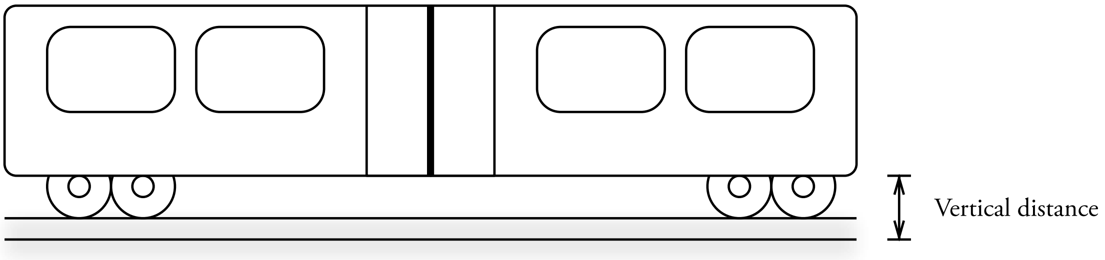

Figure 10. An illustration of the exit height/vertical distance from a train.

More data related to the passenger flow has been collected by Norén and Winér (2003) who studied the flow of people at different stations, primarily under normal conditions, see Table 5. In these studies they also examined the effect of luggage and the vertical distance between the trains and the surface. Norén and Winér (2003) observed that with increasing vertical distance the passenger flow decreased. Furthermore, a decrease in the passenger flow could also be observed when people carried luggage. Norén and Winér (2003) suggest that this could be due to the inability to exit a train side by side due to the luggage, as well as the fact that people tend to move slower when carrying luggage. Of the two factors affecting the evacuation, the most important factor was the vertical distance (Norén & Winér, 2003).

Problems related to the opening mechanism of the train doors was observed in the experiments carried out by Oswald et al. (2005) where passengers evacuated from a smoke filled rail carriage. The participants did not easily understand the opening mechanism and the instructions provided. When the doors finally where opened passengers left the train one by one, even though there were enough space for more than one person to leave at a time. In surveys filled out after the experiment a great proportion of the passengers complained about the exit height of 0.64-0.67 metres (the vertical distance between the train and the surface, see Figure 10). Even though the participants represented a rather young group the video documentation showed that more than 50% of the participants had problems with the drop (Oswald, et al., 2005).

Prior to the disembarking of the train it was observed that passengers had to rely on their sense of touch inside the train due to the smoke density. This was done by feeling the side partitions and handrails with their hands and by cautiously moving their feet to feel the floor elevations. This type of behaviour have also been observed in past accidents as well as other experiments where smoke have been present or the lighting conditions have been scarce (Fermaud, et al., 1995; Frantzich, 2000; Galea & Gwynne, 2000; Rohlen & Wahlström, 1996). The smoke density also made illuminated passenger information, pictograms and markings invisible. In the surveys, participants asked for better lighting systems, similar to those on aircrafts (Oswald, et al., 2005).

Oswald et al. (2008) carried out evacuation experiments from a high floor metro train in order to study the passenger flow through the exits. However, the data about the flow is not explicitly documented in their paper. Because of this no data from the experiments are summarized in Table 6, but the authors observations and conclusions are discussed here. The flows through the doors in the tunnel experiments were in the range of 0.25 p/minute and meter (which seems exceptionally low if compared to the data in Table 5). Furthermore, the authors did not observe a significant difference in the flow rates when the vertical distance changed from 0.65 to 1 metres. The participants applied three different strategies for exiting the train. Oswald et al. (2008) classified them as either "jumpers" (45%), "siders" (28%) and "sitters" (27%) and the flow rate were dependent on the strategy adopted (Oswald, et al., 2008).

In the evacuation experiments carried out by Galea and Gwynne (2000) the flow rate capacity of an overturned rail carriage was estimated. The test participants had been instructed only to disembark at the front and rear end of the train, and thus not to attempt to climb through the windows. Therefore measurements were only made at those exits. In the first experiment were no smoke was present the average flow rate at the rail exits was estimated to be 9.2 persons/minute. In the second experiment the average flow rate was estimated to be 5.0 persons/minute. The authors therefore concluded that the introduction of smoke more or less doubled the evacuation time.

Table 5. A summary of the flow of people in various experiments. Width = door width, VD = vertical distance between the train and the surface.

Train type	Width [m]	VD [m]	Flow [p/s]	Flow [p/m s]	Reference	Notes
One-storey intercity train	1.07	0.30	1.00	0.935	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
	1.07	0.30	0.682	0.637	Norén and Winér (2003)	Normal conditions. Mostly commuters, some travellers with heavy bags.
	1.37	0.50	0.952	0.694	Norén and Winér (2003)	Normal conditions. Mostly travellers carrying a lot of luggage.
Two-storey intercity train	1.27	0.30	0.788	0.620	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
	1.40	0.30	1.143	0.816	Norén and Winér (2003)	Normal conditions. Mostly commuters, some travellers with heavy bags.
	1.27	0.30	1.067	0.840	Norén and Winér (2003)	Normal conditions. Mostly commuters, some travellers with heavy bags.
	1.27	0.70	0.729	0.574	Norén and Winér (2003)	Smoky conditions. Test participants, no luggage and aware of the test purpose.
Local train	0.88	0.30	0.761	0.865	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
	0.77	0.30	0.739	0.960	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
	0.73	0.30	0.475	0.651	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
	1.27	0.30 / 0	0.717	0.564	Norén and Winér (2003)	Normal conditions. Mostly travellers carrying a lot of luggage. Two different VD on the same train.
	1.27	0.30	0.441	0.347	Norén and Winér (2003)	Normal conditions. School class.
International train	0.90	0.30	0.538	0.598	Norén and Winér (2003)	Normal conditions. Mostly commuters with briefcases or lightweight bags.
Metro train	1.20	0	1.588	1.221	Norén and Winér (2003)	Normal conditions. Only commuters, some carrying briefcases.
	1.20	1.20	0.1-0.2	0.083-0.167	Frantzich (2000)	Evacuation experiment inside a tunnel with no lighting. Emergency ladder used by some.
	1.20	1.20	0.4-0.6	0.333-0.666	Frantzich (2000)	Evacuation experiment inside a tunnel with lighting. Emergency ladder used by some.

4.4. Results related to the walking speed

The time it takes for a person to reach an exit is, among other things, dependent on the walking speed. In turn, the walking speed is strongly dependent on other variables, e.g., the type of surface, smoke density, etc. The walking speed of people evacuating have been measured in various experiments, ranging from road tunnels to rail tunnels. These results are summarized in Table 8.

In his experiments Jin (1976) measured the walking speed, even if the main purpose was to determine at what distance a fire exit sign could be distinguished. The main conclusion that he draws is that the walking speed decreases as the smoke density increases. It was observed that the behaviour became more similar to walking in darkness when the smoke density increased, meaning that the subjects used their hands touching the wall as they travelled towards the exit. Furthermore, it was also concluded that the walking speed decreased when the irritation from the smoke increased. However, of the two, Jin (1976) argues that the main factor that reduced the walking speed was the obscuration of visibility due to the smoke. In his experiments Jin (1976) also compared the no lighting situation with lighting. He suggests that a poor illumination in a corridor does not necessarily mean that people familiar with the building will be affected. However, it is likely that those not familiar with the building will be affected. By combining his own results with the results of other researchers, Jin suggests a minimum visibility and smoke density in an evacuation, see Table 6.

Table 6. Recommended minimum visibility and smoke density for a safe evacuation. (Jin, 1976)

Degree of familiarity	Visibility [m]	Smoke density (extinction coefficient) [m^{-1}]
Unfamiliar	15-20	0.1
Familiar	3-5	0.4-0.7

A couple of years later Jin (1981) carried out new experiments to examine emotional instability in smoke filled environments. The purpose was to see at what maximum smoke densities that an evacuation still could continue. Jin (1981) concludes that the smoke density threshold for people that are unfamiliar with a building is dependent mainly on the reduced visibility and the irritation caused by the smoke, thus causing an emotional instability. However, for people familiar with a building the smoke density threshold is mainly dependent on the extent to which they physiologically cannot tolerate the smoke (causing irritation and suffocation). Based on the results Jin (1981) choose to update the values presented in Table 6, the new values for minimum visibility and smoke density are presented below, see Table 7.

Table 7. Recommended minimum visibility and smoke density for a safe evacuation. (Jin, 1981)

Degree of familiarity	Visibility [m]	Smoke density (extinction coefficient) [m^{-1}]
Unfamiliar	13	0.15
Familiar	4	0.5

Heskestad's (1999) re-analysis of the five Norwegian experiments revealed that movement speed is relative independent of the luminance level of the exit signs. In the span 0.2-30 cd/m^2 only small increases in movement speed was achieved. Between 20 and 30 cd/m^2 there was even a dip in speed, but Heskestad (1999) argues that this might have been caused by light reflection since white smoke was used in the experiments.

Frantzich (2000) measured the walking speeds at different points in the tunnel during his experiments in the Stockholm metro. The results from the experiments demonstrated that the walking speeds were increasing much in comparison with the cases “no lighting” and “emergency lighting”, see Table 8. However, Frantzich (2000) concludes that as long as lighting is provided the brightness plays a minor role. In the case where there was no lighting at all in the tunnel it was observed that people held hands to avoid getting lost, a type of behaviour that have also been observed in past accidents, e.g., the Zürich metro fire (Fermaud, et al., 1995; Frantzich, 2000).

In the experiments in the Benelux tunnel, Norén and Winér (2003) measured the walking speeds of the evacuating participants. The mean walking speed was estimated to be 1.37 m/s with a standard deviation of 0.55 m/s. Furthermore, Norén and Winér (2003) concluded that the slope gradient of 4.5% did not affect the walking speed.

Measurements of the walking speed was also done by Frantzich and Nilsson (2004) in their laboratory experiments in a road tunnel. The walking speed varied between 0.2-0.8 m/s for test participants, but more interesting was the observation that the participants seemed to walk faster when they followed the tunnel wall. Furthermore, it was observed that 80% of the test participants followed a wall sometime during the experiment. Answers in the questionnaires revealed that this type of behaviour was explained by the fact that it was easier to find the way inside the tunnel. Video recordings also revealed that participants used their hands to look for emergency exits by using their perception of touch. It was observed that the walking speed decreased with an increasing extinction coefficient, as have been suggested by Jin (1976).

In the experiments carried out by Oswald et al. (2008) no measurements of the walking speeds were done. However, it was observed that the evacuation in the tunnel was strongly influenced of the people walking on the sideway, as well as the people still disembarking the train. If the sideway is not wide enough there will be queues and the ability for a person is greatly reduced. Instead a person is forced to “go with the flow”.

Table 8. A summary of measured walking speeds from various experiments. Mean = mean walking speed, Std = standard deviation. For the exact relationships between walking speed and smoke density see the original references.

Reference	**Mean [m/s]**	**Std [m/s]**	**Notes**
Norén and Winér (2003)	1.37	0.55	Road tunnel with some smoke.
Frantzich (2000)	0.5-1.0	-	Metro tunnel with smoke. No lighting.
Frantzich (2000)	1.0-1.45	-	Metro tunnel with smoke. Emergency lighting.
Frantzich and Nilsson (2004)	0.2-0.8	-	Road tunnel experiments with irritant smoke. With and without lighting.

4.5. Results related to the choice of exits

There are several factors influencing on the choice of an exit, some of which have already been discussed in the chapter about theoretical research. The results in this section are divided into subsections in terms of how the experiments have been carried out and what the purpose have been to examine.

4.5.1. Design of exit signs

Some interesting observations regarding the size and illumination of emergency exit signs was made in the experiments carried out by Jin et al. (1991). Basically, an exit sign was more conspicuous the larger and brighter it was (from 0-3000 cd/m^2). However, by adding a flashing light in the exit sign the conspicuousness was further improved. In the experiments three different sizes of exit signs were used, and it was concluded that adding a flashing light to the medium sized sign (20 x 60 cm) achieved a bigger improvement than making it larger.

The performance of different lighting systems was examined in Heskestad’s (1999) re-analysis of the five Norwegian experiments. Primarily two kinds of low location lighting (LLL) systems were analyzed. An electrical powered (EP) system and a photoluminescent (PL) system. A comparison of these systems was made against an electrically powered cold cathode system. By computing the probability of making the right decision, i.e. choosing the right path in an evacuation route, an average probability could be calculated for each of the systems, see Table 9.

Table 9. The probability of making the right decision in an evacuation for different illumination systems (Heskestad, 1999).

	LLL (EP or PL)	**EP cold cathode or tactile systems**	**Combination of EP cold cathode and tactile systems**
Probability of making the right decision	0.69-0.79	0.90	0.98

Thus, a combination of a tactile system and a electrically powered cold cathode system performed best when test participants were instructed to evacuate in the test setups. However, the above numbers are the probability of making a correct decision at one choice of path. To calculate the overall probability of finding the way out, the equation $p = p^n$ has to be solved, where n is the number of decision elements (Heskestad, 1999). The most interesting conclusion that Heskestad

(1999) make of this is that the accumulated probability of a wayfinding system with low performance rapidly diminishes, as can be demonstrated in Figure 11 (Heskestad, 1999).

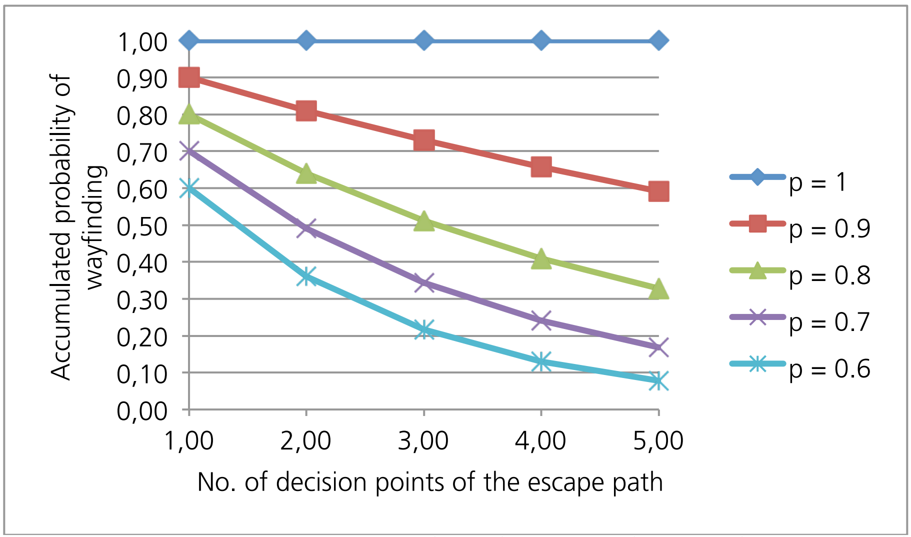

Figure 11. The accumulated probability of way finding as a function of the number of decision point of the escape path (Heskestad, 1999).

That emergency signs are highly associated with safety in an emergency evacuation are concluded by McClintock et al. (2001). However, during everyday conditions building occupants do not notice them, as they tend to blend in with the rest of the environment. McClintock et al. (2001) try to explain this behaviour with a term called “learned irrelevance”, meaning that if a person is continually exposed to a stimulus (in this case an emergency exit sign) he or she is likely to ignore it after a while because the information is irrelevant. Consequently, this leads to an underuse of emergency exit signs. This type of behaviour is a part of the affiliative model, which has been discussed in a previous chapter, see section 3.3. In an attempt to increase an exit signs “attention capturing ability” blue flashing lights were added to the exit signs. When asked to compare this technical solution to other solutions a majority of the participants rated the blue flashing lights as the best system (McClintock, et al., 2001).

In a previous chapter it was described that the participants in Frantzich and Nilsson’s (2004) road tunnel experiments used their perception of touch rather than their vision when looking for exits, see section 4.4. However, most tunnels only have emergency exits on one side. This means that when a person follows a wall inside a smoke filled tunnel and is looking for an exit by feeling the wall, an exit at the opposite side of the tunnel might be missed. Frantzich and Nilsson (2004) present two solutions to this problem. Either emergency exits should be installed at both sides of a tunnel or a technical solution as the one in Figure 12 could be used.

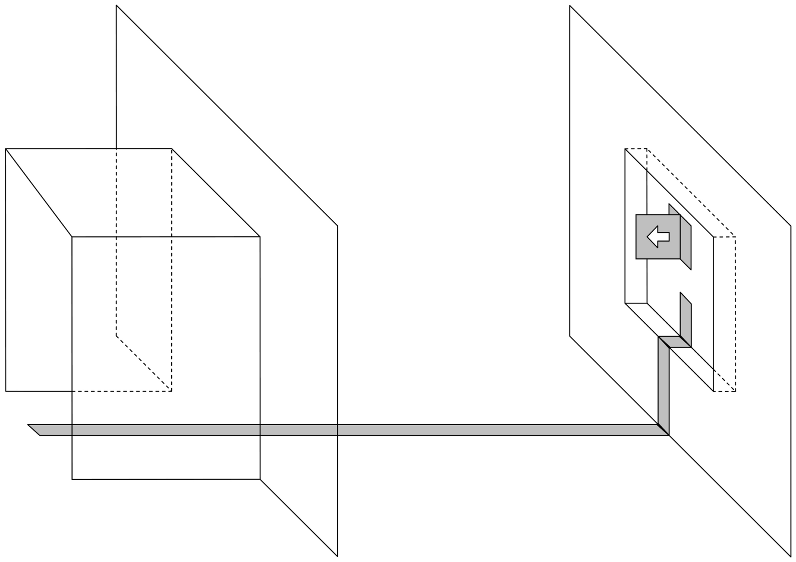

Figure 12. A design suggested by Frantzich and Nilsson (2004) as an alternative to emergency exits on both sides inside a tunnel. By permission (Frantzich & Nilsson, 2004).

To further improve the design of technical solutions, in this case emergency exit signs, Nilsson et al. (2005) conducted both laboratory experiments in a corridor and hypothetical scenario experiments were test subjects were instructed to grade different way-finding systems. Based on the experiments the authors conclude that when emergency signs are equipped with either flashing lights or strobe lights they are chosen more frequently (compared to the traditional emergency exit design), as also has been shown by McClintock et al. (2001). The authors therefore argue that by actively highlighting an emergency exit it might be possible to break evacuee's tendency to move to familiar exits (a behaviour that has been described above). Furthermore, the hypothetical study showed that green light was the most appreciated colour and many participants claimed it was because it is interpreted as safety and go (Nilsson, et al., 2005).

The effects of green flashing lights were investigated in the evacuation experiments described by Nilsson et al. (2008). One of the objectives was to examine whether or not green flashing lights at an emergency exit sign would perform better compared to a traditional exit sign. The results showed that in the office building the emergency exits with the flashing lights were used slightly more than the exits equipped with traditional exit signs, however, the difference was not significant. In contrast, the exits equipped with the flashing lights were used by almost all visitors in the cinema theatre. Thus, a difference could be observed between the two types of buildings. In the office building, the environment is much brighter compared with the cinema theatre and Nilsson et al. (2008) argues that the contrasting potential thus is bigger in the cinema theatre, making the emergency exit signs stand out more than in the office building. However, based on the results from the experiments, Nilsson et al. (2008) argue that green flashing lights can be used to influence people's choice of exit. However, to what extent the flashing lights will influence people are strongly linked to the building's setting (Nilsson, et al., 2008).

4.5.2. Social Influence and Information

That discussions and disagreements among passengers on a train can influence the choice of an exit and was highlighted in the experiments carried out by Frantzich (2000) in the Stockholm Metro. There, discussions regarding which way to evacuate seem to have started as soon as the participants had disembarked the train in both experiments. The discussions and the lack of agreement seem to have created a situation where unnecessary crowding appeared. In the experiment where no information was provided to the passengers 75% of the participants chose to evacuate in the direction of where they came from. Signs informing the participants of distances to stations in both directions were provided, but only on one side. Thus, only those who disembarked the train at that side could use them. However, all of them did evacuate towards the closest station (Frantzich, 2001). To overcome the problem discussed above Frantzich (2001) concludes that the train driver in an emergency situation must be very clear when informing the passengers about what they are expected to do and in which direction to evacuate relative to the direction of travel.

In the experiments conducted in the Benelux tunnel by Boer and Veldhuijzen van Zanten (2005) it was observed that people were unwilling to travel past a burning obstacle, in this case the HGV, even though there were emergency exits behind it. Despite this, 94% of the drivers selected the nearest exit when evacuated. Those who did not pick the nearest always walked forward to the next (Norén & Winér, 2003).

In contrast to Norén and Winér's (2003) experiments only 22% of the participants walked to an emergency exit in the laboratory road tunnel experiments carried out by Frantzich and Nilsson (2004). The rest exited the tunnel either at the tunnel end or at the tunnel entrance. However, in the questionnaire 38% stated that they had noticed an emergency exit. Frantzich and Nilsson (2004) conclude that 59% of the participants who saw an emergency exit choose not to use it. It is argued that the white floor markings were not seen due to the white artificial smoke. However, this doesn't explain why the other two wayguidance systems failed. Frantzich and Nilsson (2004) argues that this might be because the test participants did not have any experience of the systems, did not know what they meant and therefore did not use them.

In the road tunnel experiments described by Nilsson et al. (2009) it was observed that almost all of the test subjects used the closest emergency exit, which is similar to the observations made by Norén and Winér (2003) in the Benelux tunnel. Furthermore, the wall signs pointing in other directions were sometimes discarded (Nilsson, et al., 2009). This type of behaviour can to some extent be explained by social influence, which has been discussed above, see section 3.4. The results from the experiments showed that green flashing lights at the emergency exit had a positive effect on the choice of emergency exits when they were noticed. However, Nilsson et al. (2009) concludes that only a handful of the test subjects mentioned that they saw the lights. Therefore it is discussed if maybe the flashing lights is seen as an integrated part of the emergency exit and therefore is not remembered as an outstanding feature (Nilsson, et al., 2009).

5. Discussion

This report contains information from a great amount of literature related to fire evacuation in underground transportation systems. Past accidents, theories and models on human behaviour and finally empirical research have been studied and the most important observations and results have been summarized. A brief discussion to sum up these observations and results is presented below.

If people are not to be injured or killed in the event of a fire in underground transportation systems, it is of uttermost importance that they are able to evacuate before conditions become untenable, e.g., passengers need to understand that they should evacuate and not wait for the next train, ticket collectors need to understand that they should not continue to let people inside a station, and so on. In order to prolong the margin of safety, see Figure 7, either effort can be made to increase the ASET (for instance by installing sprinklers) or to reduce the RSET. Due to the framework of this report, this discussion will mainly focus on the factors that can reduce the RSET.

To describe evacuation with the egress time-line model, which has been demonstrated in Figure 7, is in fact to make a complex sequence of behaviours somewhat easier to understand. Although the egress time-line model is a valuable tool for the fire safety design of underground transportation systems, it is an engineering tool that provides limited guidance towards the understanding of human behaviour. It does not take into account the underlying complex sequences of behaviours that an evacuation includes. To understand these underlying sequence of behaviours it is better to use the behaviour sequence model developed by Canter et al. (1980), see Figure 8. Though, it is important that the behaviour sequence model is interpreted as a cycle and not as something static, i.e., an evacuee does not receive information only once during an evacuation but probably many times as he or she moves along an evacuation route; the information is updated. Furthermore, when a person has decided to evacuate via a certain route, new information could mean that the route is changed or that the person decides to withdraw. This is not included in the egress time-line model.

The way a person will interpret, prepare and act on the information he or she receives about a danger will most likely depend on the role he or she has adopted. This has been demonstrated in the fires at the King's Cross station and the Zürich Metro fire, but also in investigations of domestic, multiple occupancy and hospital fires (Canter, et al., 1980; Donald & Canter, 1990; Fermaud, et al., 1995). In the fire at the King's Cross station it was observed that people were reluctant to initiate an evacuation. This could partly be described by a role keeping behaviour. A passenger who enters the station with the objective to travel from point A to point B does not want to give up that objective because it interferes with the rules associated to the role as a passenger. In the same way, an employee working in an underground facility is not likely to abandon his or her objective as, e.g., a ticket collector, but will continue to act as instructed until enough cues are identified to change that behaviour. The King's Cross fire also demonstrates that the role a person has prior to a fire affects the behaviour during the fire. In the fire staff members and the police acted differently compared to the passengers, i.e., the relative roles in the non-fire situation was maintained during the fire. The staff members and the police took the role of authority and instructed the passengers. In contrast, when enough information about the fire was received, the passengers evacuated.

If a person in an underground transportation system is to abandon the objective related to his or her role in the event of an emergency, i.e., the objective to travel from A to B for a passenger, information is a prerequisite. However, it has been demonstrated that the sounding of a single alarm, or even the observation of smoke, is not always enough to get people to initiate an evacuation (Donald & Canter, 1990; Proulx & Sime, 1991). Therefore, information to users of underground transportation systems should include information about what is happening and how they are supposed to react to that information. Furthermore, the information needs to be clear and coherent and it needs to be provided fast. Coherence is particularly important to avoid conflicts and confusion. For example, if an alarm is activated at an underground station and the traffic information signs are still saying "the train will arrive in five minutes" it is likely that a change of objective will not occur because some cues are telling people that the traffic is still operating as usual.

The ability to provide occupants in a building with fast, clear and coherent information is in turn dependent on the emergency management. It could be expected from staff working in an underground facility that they should contribute in the evacuation in the event of a fire. Furthermore, staff working for an underground operator needs to have clear responsibility areas in order to respond to an emergency. They need to be well educated in order to know what to do. Exercises could be one way of preparing for an emergency as well as educating staff. In view of the fact that it has been observed that the police to a greater extent have the possibility to get people to abandon their roles as passengers and initiate an evacuation (compared to underground staff) it is important to include them, as well as other actors in an emergency, in the exercises. The police should be prepared to mount the role as head of an evacuation, which in turn demands knowledge of public places and communication between the police and an underground operator.

One way to provide users of underground transportation systems with information could be via loud speakers. However, messages from loud speakers might be hard to make out due to the challenging acoustic environment in a tunnel which have been demonstrated in experiments by Nilsson et al. (2009). But even though the messages were hard to make out it provided the occupants with some information about the fire, which was an important factor for their decision to leave their car. More specifically the information made them look for more information. The behaviour can be described with the behaviour sequence model in Figure 7. As the participants received information about the fire, in this case a pre-recorded message that was difficult to make out, they interpreted it, which led to an investigating behaviour. Although the information was not enough to initiate an evacuation immediately, it demonstrates that it is important as it initiates a behaviour that might lead to an evacuation when more information is gathered.

Informative Fire Warning (IFW) systems have been demonstrated to reduce the overall movement time, however, no testing have been carried out in underground transportation systems (Bellamy & Geyer, 1990; Canter, et al., 1988). The purpose of an IFW system is to guide evacuees along a certain route, or to inform them to avoid places at which a fire is burning. However, some scepticism should be aimed at efficiency in complex buildings. In a complex facility, e.g., an underground station, much information has to be provided in such a message in order to inform all occupants which routes to take and which to avoid. However, the use of an IFW system inside a tunnel could provide occupants with very valuable information, i.e., on which way they should go. Past accidents have shown that occupants do not always evacuate the most efficient way. Furthermore, inside a tunnel the environment is not as complex as a station. The evacuees actually only have two ways to go, either right or left. If an IFW system is installed and the operator acts fast, such a system could provide evacuees with very valuable information on which direction to move.

Providing users of underground transportation systems with fast, clear and coherent information will probably also be efficient in reducing the negative effects of social influence. It is likely to believe that there often are much people present at the same time in an underground facility and on trains, and in an emergency situation where information is scarce it has been demonstrated that people do not act because they are afraid of standing out or to make fools of themselves (Deutsch & Gerard, 1955; Latané & Darley, 1968). Instead, people look at each other when there is uncertainty about what to do and where nobody else reacts a person is likely to adopt the same behaviour.

Along with the traditional fire cues it has been concluded that information could help get a passenger to abandon his or her objective as a passenger and instead initiate evacuation. In addition, fast, clear and coherent information could also help occupants in an underground facility in terms of choosing other ways to exit than those familiar to them. Previous in this report, see section 3.3, it has been argued that people are likely to evacuate in routes that are familiar to them in an emergency (Sime, 1983, 1984, 1985b). Thus, the choice of an exit is not solely dependent on the proximity of it, but also on a person's role and his familiarity with the facility. Information could to some extent help people break the pattern of behaviour and when information is given about an exit or the location of a fire there is at least a chance that the person will choose another exit. That people have a tendency to choose familiar exits in evacuation situations should furthermore be kept in mind during the design phase to ensure that the environment supports evacuation. For example, it might be better to design an underground station with two everyday exits, which are also designed as evacuation routes, instead of one everyday exit, which is not designed as an evacuation route.

However, sometimes the use of emergency exits unfamiliar to the users of underground transportation systems are impossible to avoid. In this case it is important to realise that extra measures or systems have to be in place to ensure that the exits are used. Experiments that have been carried out have demonstrated that emergency exits need to be designed so that they fast and easy will be recognized as emergency exits (Sixsmith, et al., 1988). They need to have affordances that support the user so that they send out the message of openness. Experiments have also shown that by adding outstanding features, such as flashing green lights, can increase the use of emergency exit doors (Nilsson, 2009). It is likely that they do so because of the adding of a sensory and a cognitive affordance to the door.

Another important observation in terms of exit choice is that the probability of making the right decision (in terms of choosing which way to evacuate) is very dependent on the type of illumination system used (Heskestad, 1999). Evacuating inside a tunnel more or less means evacuating in a complex environment, and if the number of decision points is many and the illumination system is bad it is clear that an evacuee probably not will exit the facility in the most efficient way.

It is not only the emergency exit doors at the stations and inside the tunnels that need to be provided with affordances that supports the user. Both in past accidents and in experiments problems with opening train doors have been identified (BBC News, 2003; Bergqvist, 2001; Carvel & Marlair, 2005; Larsson, 2004; Oswald, et al., 2005; Rohlen & Wahlström, 1996). In some cases the difficulties could be related to an electrical failure but mainly the issue has been to identify and to operate the door opening mechanism. If a train for some reason comes to a stop inside a tunnel it is imperative that passengers can open the doors easily. What can happen if that possibility is not given to the passengers can be illustrated by the fire in Kaprun (Bergqvist, 2001; Larsson, 2004). Emergency door openers should be designed so that they easily could be used, even in the event of electrical failure and also without the user having to read long instructions. Furthermore, the emergency door openers should preferably be placed in proximity of the doors and be clearly marked so that they can be identified in stressful situations, which could involve a lack of lighting.

Last, but not least, something should be said about lighting conditions and the surface on which evacuees are forced to travel on inside tunnels. It may seem obvious that the movement speed decreases when the lighting is decreased, but it is still worth mentioning as this phenomenon has been identified in both experiments and past accidents. In the design of a underground transportation systems this must be considered. For instance, it might be wise to put lighting closer to the floor inside a tunnel because then chances that the lighting will be impaired by smoke from a fire are reduced. The same goes for placing emergency exit signs. If placed high they will probably be harder to see if there is a fire in the tunnel, which means that evacuees could miss a certain exit. If the lighting is obscured it will also become harder for the evacuees to walk inside the tunnel, due to the (often) uneven surface. As well as considering the placement of light sources and emergency exit signs (and other technical installations), consideration should also be given to what material to use inside the tunnels as surface for walking.

6. Conclusions

From the reviews of past accidents, theories and models of human behaviour and the empirical research it is clear that human behaviour in emergencies and fire is complex and that it sometimes can seem irrational to a person studying the behaviour in retrospect. However, to use one word, e.g., 'panic', is to simplify a far more complex matter and will probably lead to a misunderstanding of the course of events taking place in an evacuation. Instead, the adoption of a clear theoretical framework can aid the understanding of fire evacuation in underground transportation systems. This theoretical framework should include the behaviour sequence model, the affiliative model, social influence and the theory of affordances.

One of the major issues related to fire evacuation in underground transportation systems is that people often are reluctant to initiate an evacuation. This is explained by a number of factors:

- That people tend to maintain their roles (e.g., as passengers)
- The lack of fast, clear and coherent information
- The ambiguity of the cues from the source of danger (e.g., a fire)
- The presence of others, i.e., social influence

Furthermore, when an evacuation has been initiated there are other factors that affect the efficiency of the evacuation. Some of the problems that has been identified are:

- Problems with the door-opening mechanism on trains
- The vertical distance between the train and the tunnel floor
- That people tend to evacuate through familiar exits
- Lack of lighting
- Uneven surfaces inside the tunnels

All of the factors above are important and together they will affect the outcome of an accident, and therefore they need to be considered in the fire safety design of underground transportation systems. The present review has, by adopting the theoretical framework, also presented solutions to some of the problems above.

Fifty years ago it was believed that providing occupants with information about an accident could trigger 'panic'. Today we know that is not the case, and in contrast it is suggested that occupants should be provided with fast, clear and coherent information. This information could help people to initiate evacuation, but could also help people to find the ways to safe locations without having to evacuate via familiar routes and to reduce the negative effects of social influence. However, providing users of underground transportation systems with this type of information demands an emergency organisation, where staff is educated and has clear responsibility areas.

When an evacuation has been initiated, technical installations are required if the evacuation is to proceed with efficiency. For instance, adding affordances that supports the user to emergency exits inside a tunnel or a station (such as green flashing lights) could help overcome a person's will to exit via a familiar route. Furthermore, good lighting conditions and an escape path free of obstacles is also a prerequisite for a smooth evacuation.

7. Future research

In this report recommendations on designs and solutions related to fire evacuation in underground transportation systems have been discussed, and many recommendations on how to make evacuation more efficient have been presented. However, problems related to this area have also been highlighted and in this chapter suggestions for future research dealing with these problem areas are presented.

A big issue related to emergency evacuation has been demonstrated to be the role keeping behaviour of people. A passenger waiting for a train to arrive does not necessarily start evacuating just because he or she hears the sound of an alarm. However, research has demonstrated that fast, clear and coherent information could be one way to influence the behaviour and to get passengers to initiate evacuation. Studies on use of abbreviations and message length have been carried out. In addition, the use of IFW systems has demonstrated that the overall evacuation time could be reduced. However, this research was carried out almost thirty years ago and new technical solutions have since been developed. A comprehensive system, involving traffic information signs and TV screens, directive public announcements through public announcement systems, and involvement of the staff have not yet been examined and it would therefore be interesting to study the overall effects of such a system.

Designing emergency exit signs with affordances that support the user, e.g., green flashing lights, have been shown to be another way to influence the behaviour of underground. It has also been demonstrated that users of underground transportation systems seldom use fire equipment, e.g., fire extinguishers and emergency telephones. Maybe the emergency exit design could be applied when marking out fire equipment. However, more studies to find the optimal design in underground facilities are recommended for such a solution.

No studies have been carried out considering the possibility for people with disabilities to evacuate in the event of fire in underground transportation systems. Today it is more and more expected that everyone should have access to the same services in society and thus efforts have been made to help people with disabilities to use, e.g., the metro system. However, the same amount of attention have not been paid to the safety and it is therefore of much interest to study the possibilities for a person with a disability to evacuate, both in tunnels and stations. Some studies have actually looked at the effects of emergency ladders onboard trains, how they were used in experiments and so on. However, it is not likely that an emergency ladder is enough to provide help to a person in a wheelchair if a train comes to a stop inside a tunnel. If that person manages to exit the train then more problem arises, namely the movement issue inside the tunnel. Not only would it demand a lot of human power to travel inside a tunnel in a wheelchair (if at all possible), a person travelling in a wheelchair is also likely to prevent an efficient evacuation for all other people in that tunnel due to the often small escape routes. Efficient solutions will demand that a lot of research is carried out, and the area has a great development potential.

It has become clear that a comparative study of different types of surfaces inside tunnels related to evacuation have not been carried out. Evacuation related problems inside tunnels, e.g., risk of stumbling, slow movement speeds, inaccessibility for wheelchair users, etc., have been identified in this review and it would therefore be interesting from a cost-benefit perspective to see if a certain type of surface inside a tunnel is more effective than another. This would in turn demand that experiments studying the movement speeds on different surface types are carried out.

From a cost-benefit perspective it would also be interesting to examine the effects of emergency education and regular exercises in terms of emergency management in the event of an accident in an underground transportation system. It would be interesting to see if positive effects can be identified when the staff have received proper training and participated in evacuation drills. However, a prerequisite for this kind of study is that an underground operator have the ambition and the resources to implement this kind of training in a longer perspective, e.g., a five year period, and that the effects thereafter are measured.

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