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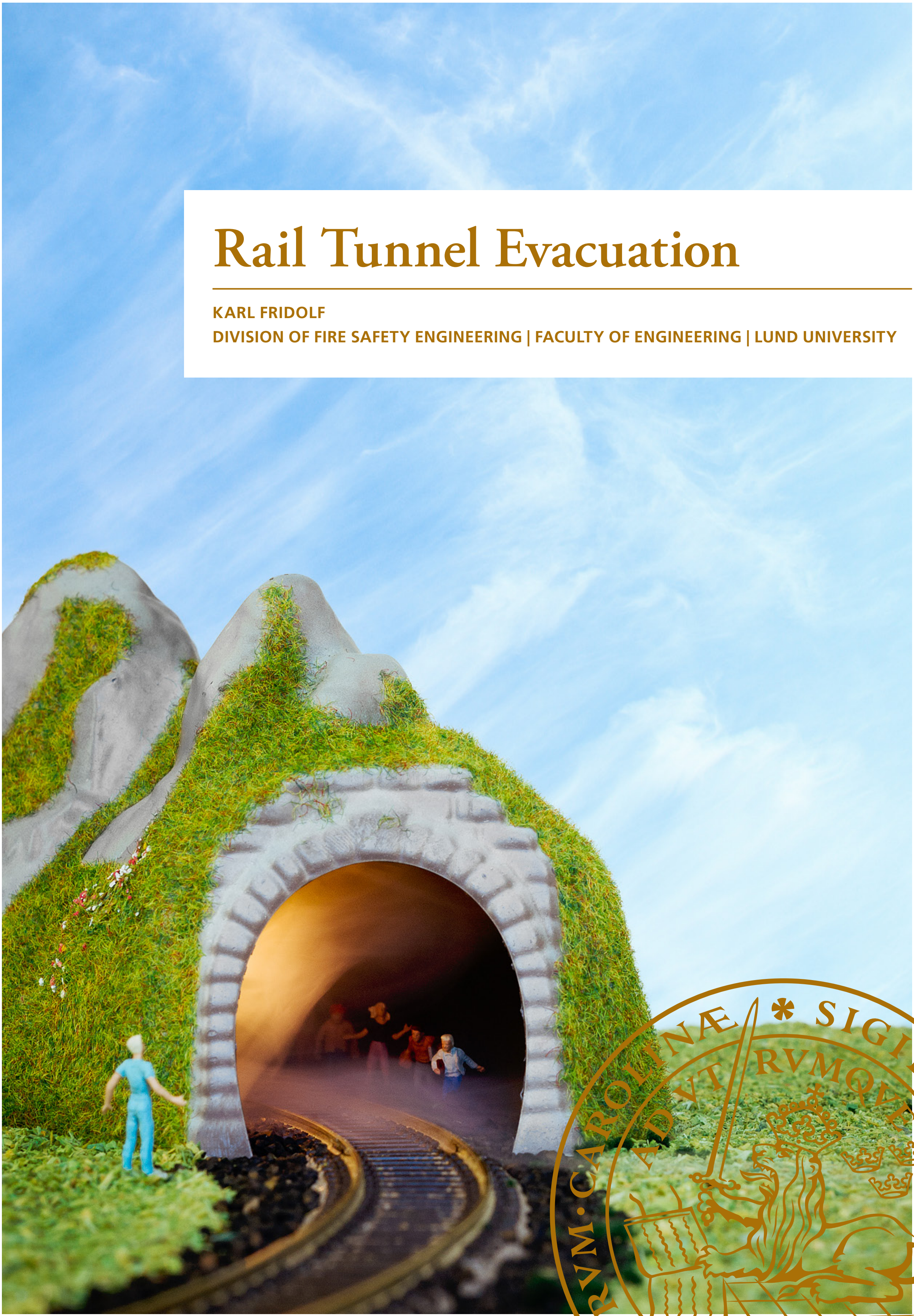

Rail Tunnel Evacuation

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DIVISION OF FIRE SAFETY ENGINEERING | FACULTY OF ENGINEERING | LUND UNIVERSITY

Rail Tunnel Evacuation

Karl Fridolf

LUND UNIVERSITY

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Rail Tunnel Evacuation

Abstract

In this thesis, human behavior in rail tunnel fires is explored. Descriptive knowledge is presented related to the evacuation of passenger trains, and the subsequent tunnel evacuation to a safe location. More specifically, a theoretical framework that can aid the understanding of human behavior is identified, and its applicability to rail tunnels is demonstrated. In addition, new empirical data on the flow rate capacity of train exits during evacuation in rail tunnels, as well as on walking speeds in smoke free and smoke filled rail tunnels, is presented. Finally, a number of technical installations that may facilitate orientation, movement and exit choice in rail tunnels are suggested. The findings are presented in relation to previously conducted empirical studies, and a discussion is also made on how the findings can be used in application and design.

Key words
Human behavior in fire, evacuation, underground rail transportation system, metro, tunnel, train, experiment, flow rate of people, walking speed, smoke.

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Rail Tunnel Evacuation

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I am also grateful to my previous and current head of divisions. Robert Jönsson, you saw me and showed that you believed in me during my time as a graduate student. Thank you for this, and for providing me with a tremendous work environment during my first years as a postgraduate student at the Division of Fire Safety Engineering and Systems Safety. I would also like to thank Patrick van Hees. Patrick, I am very grateful for your support during the later stages of my postgraduate studies, and for encouraging me in my development towards becoming an independent researcher. Finally, a warm thank-you is directed to Lars Boström. Lars, I want to thank you for believing in me and what I do, and for enabling me to come to SP Technical Research Institute of Sweden prior to the finalization of this doctoral thesis. I also want to thank you for your valuable comments during the finalization of this work.

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Wahlqvist, a dear friend and an excellent researcher, with whom I had the privilege to share an office during most of my time as a postgraduate student. Jonathan, you always took the time to answer a question or discuss a specific matter, and for that, I am truly grateful. I would also like to particularly thank Enrico Ronchi, an expert within his field. Enrico, you have often felt like a co-supervisor to me with all your support and valuable comments. Furthermore, I would like to thank Kristin Andrée, John Barton, Franz Evegren, Rita Fahy, Jonatan Gehandler, Sven-Ingvar Granemark, Samuel Grindrod, Haukur Ingason, Nils Johansson, Axel Jönsson, Fredrik Nystedt, Marcus Runefors, Michael Strömgren, Stefan Svensson, and David Winberg for their respective contributions.

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Summary

Rail tunnel fires are rare, but can lead to disastrous consequences in terms of lives lost and injured people. This is particularly true when passenger trains cannot transport people to a safe location, but instead have to be evacuated in the tunnel. In such an event, people will have to rely on their own ability to evacuate to a safe place. This involves overcoming a number of obstacles, both mental and physical, including making a decision to evacuate, evacuating the train to track level, and finding a way to safety in the unfamiliar environment that a rail tunnel represents.

A crucial safety-related aspect of a rail tunnel is the possibility of a safe escape. In order to avoid devastating accidents in the future, it is therefore necessary to consider human behavior aspects both during design and operation of rail tunnels. Unfortunately, information and data about human behavior in rail tunnel fires are scarce. The overall objective of this thesis is, therefore, to increase the knowledge on rail tunnel evacuation in the event of fire.

To meet this objective, a research strategy was selected for exploring the field of rail tunnel evacuation, and for generating descriptive knowledge. Empirical data were collected in case studies and experiments, and were used to describe different parts of a rail tunnel evacuation. This led to the identification of a theoretical framework for facilitating the understanding of human behavior in the event of a fire. In this thesis, the framework is presented and its applicability to rail tunnels is demonstrated. The framework includes four generally accepted theories and models of human behavior in building fires, and can be used to describe people's sequence of behavior, how contextual roles affect that sequence of behavior, why people are likely to move to familiar places and people, and how people influence each other in a rail tunnel fire.

In addition, new empirical data on the flow rate capacity of train exits during evacuation in rail tunnels, as well as data on walking speeds in smoke-free and smoke-filled rail tunnels, are presented. The data have been derived in both laboratory and field evacuation experiments using human participants. Finally, a number of technical installations for facilitating orientation and movement, and for increasing the usage of emergency exits in rail tunnels are presented. Among other things, an emergency exit equipped with a loudspeaker installation permitting both an alarm signal and a spoken message to be broadcasted was shown to be particularly effective for guiding people to safety, both during rail tunnel evacuation in smoke-filled and smoke-free environments.

The new findings are presented together with the most important observations from previously conducted empirical studies. A discussion is also presented on how the findings can be used in application and design. In conclusion, the material presented in this thesis contributes to the understanding of rail tunnel evacuation, and the behavior of people during such events. The findings can be used to increase the level of safety for people during rail tunnel evacuations, which in turn may contribute to safer rail tunnels in the future.

Sammanfattning

Bränder i järnvägstunnlar är mycket ovanliga, men när de väl inträffar kan de leda till katastrofala konsekvenser för människors liv och hälsa. Det gäller i synnerhet när passagerartåg inte kan köras till en säker plats, utan istället måste utrymmas i tunnelmiljön. Vid en sådan händelse måste människor förlita sig på sin egen förmåga att utrymma till en säker plats. Det inkluderar att fatta ett beslut om att utrymma, att utrymma tåget till tunnelnivå och att ta sig till en säker plats i den okända miljö som en järnvägstunnel representerar.

En väsentlig del av en järnvägstunnels totala säkerhetsnivå utgörs av människors möjlighet till en säker utrymning. För att undvika förödande olyckor i framtiden är det därför nödvändigt att beakta människor beteende, både i planeringsfasen och i driftskedet av en järnvägstunnel. Tyvärr är information om hur människor beter sig järnvägstunnelbränder mycket begränsad. Det övergripande syftet med denna avhandling är därför att öka kunskapen om utrymning i järnvägstunnlar i händelse av brand.

För att uppnå detta syfte valdes en forskningsstrategi som gick ut på att utforska området, och att generera beskrivande kunskap om utrymning i järnvägstunnlar. Empirisk data samlades in i fallstudier och experiment, och användes därefter för att beskriva olika delar av en järnvägstunnelutrymning. Det ledde bland annat till identifieringen av ett teoretiskt ramverk vilket kan användas för att öka förståelsen för människors beteende i bränder. Ramverket presenteras i den här avhandlingen, och dess tillämpbarhet på järnvägstunnlar visas. Totalt inkluderar ramverket fyra allmänt accepterade teorier och modeller om människors beteende i bränder i byggnader. Det kan användas för att beskriva människors beteende i sekvenser, hur kontextuella roller påverkar dessa så kallade beteendesekvenser, varför människor tenderar att utrymma till kända platser och tillsammans med andra människor, och hur människor påverkar varandra i järnvägstunnelbränder.

I avhandlingen presenteras även ny kunskap om personflöden i tågdörrar vid utrymning i järnvägstunnlar, liksom ny kunskap om gånghastigheter i både rökfria och rökfyllda järnvägstunnlar. Informationen är framtagen i ett antal laboratorie- och fältförsök med försökspersoner. Dessutom presenteras även ett antal förslag på tekniska lösningar som kan underlätta orientering, förflyttning och användandet av utrymningsvägar i järnvägstunnlar. Bland annat har det påvisats att en utrymningsväg som utrustas med en högtalare som kan sända ut en alarmsignal följt av ett talat

meddelande är bra på att öka användningen av utrymningsvägar, både i rökfria och rökfyllda tunnelmiljöer.

I denna avhandling presenteras det nya tillskottet av kunskap i kombination med de viktigaste slutsatserna i tidigare genomförda empiriska studier. En diskussion förs också om hur resultaten praktiskt kan tillämpas. Informationen som presenteras i denna avhandling bidrar till förståelsen av hur människor beter sig när det brinner i järnvägstunnlar. Kunskapen kan användas för att öka säkerheten för utrymmande människor i järnvägstunnlar, vilket kan bidra till säkrare järnvägstunnlar i framtiden.

Contents

Introduction

In 1860, the Nyboda rail tunnel in Sweden opened after nearly two years of construction (Bergman, Nay, & Mörner, 1870; Björkman & Ekström, 2011). It was the first rail tunnel ever to be built in Sweden, and it consisted of a single track tube, approximately 280 meters long; see Figure 1. Since then, the number of rail tunnels has steadily increased in Sweden, as well as in many other countries around the globe (Beard & Carvel, 2012, p. xiii). This is especially true for recent years, during which the number of rail tunnels has increased rapidly. The reasons for this are many (Bonnett, 2005; Haack, 2003; Holthuis, Jovanovic, Wijnands, & Hoving, 2014; Vägverket, 2005). Tunnels do, for example, offer an efficient alternative compared to leading rail traffic over high geographic altitudes. In fact, it may be the only alternative as overly steep gradients may prohibit rail traffic above ground. In addition, tunnels are often considered as appealing alternatives to bridges where waterways form obstructions to land-based traffic, or in other highly valued natural surroundings. Rail tunnels are also built to achieve more efficient traffic solutions in heavily populated urban areas, often as part of large metro systems. This means that conflicts with other land-based traffic modes can be avoided, and that towns can be made more accessible for pedestrians.

However, rail tunnels are not only increasing in numbers. During recent years, there has also been a trend to build exceptionally long tunnels. Two examples are the Channel Tunnel (50.5 km) between France and the United Kingdom, which opened in 1988, and the Gotthard Base Tunnel (57.1 km), which is currently being constructed. In addition, rail tunnels are today being built deeper below street level than before. This is particularly true in heavily populated urban areas, and can be illustrated by both existing and future planned underground stations in these tunnels. One example is the existing El Coll – La Teixonera station in the Barcelona metro, which is located approximately 70 meters below street level. Another example is the planned location of the Sofia station, a future underground station in the Stockholm metro, approximately 100 meters below street level (Stockholmsförhandlingen, 2013).

Naturally, rail tunnels being constructed today can still be relatively simple with regards to layout and design. However, engineering principles have developed much since the construction of the Nyboda rail tunnel. Apart from the fact that this development allows both longer and deeper rail tunnels to be built, it has also enabled several rail tunnels to be interconnected into large underground rail transportation systems. Typically, this is exploited in heavily populated urban areas, in which metro systems are built to relieve urban traffic and transportation. Such systems, which sometimes are termed multifunctional buildings (Nilsson, 2013, p. 1), may also include many different societal functions and/or occupancies within the same facility.

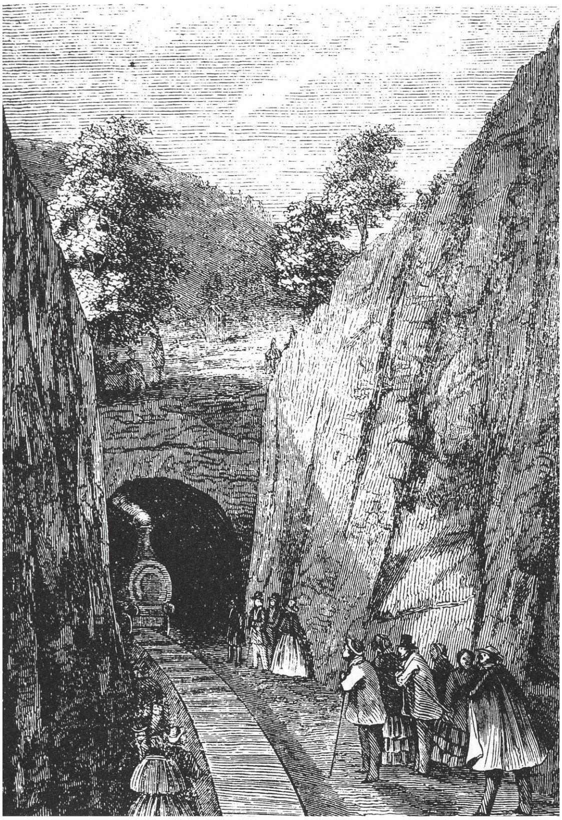

Figure 1. Illustration of the Nyboda tunnel, which was the first rail tunnel ever to be built in Sweden. Illustrator unknown. Used with permission from Hans Björkman.

Obviously, there are many advantages to exploiting the underground to build rail tunnels. However, the trend to build more, longer, and deeper rail tunnels, and the possibility to include them as parts of multifunctional buildings have increased both their use and complexity. In addition, rail tunnels introduce a number of unique risks to life safety. The consequences of a fire in a rail tunnel can, for example, be far more severe than for a fire in the open. There is, therefore, an increasing demand on society to handle fire and life safety issues in these facilities. To some extent, this can be done by adopting fire and life safety design concepts developed for buildings above ground. However, rail tunnels are in many aspects unique environments, which will affect the possibilities of a safe escape, for instance. This is illustrated by a comparison with buildings above ground, which reveals that (Fraser-Mitchell & Charters, 2005; Haack, 2003; Ingason, Li, & Lönnermark, 2015; Shields & Boyce, 2004):

- Fires in rail tunnels may develop more rapidly, and release significantly more energy.
- Fires in rail tunnels may generate aerodynamic disturbances, causing smoke and hot gases produced by the fire to spread to remote parts of a tunnel system.
- Formation of a smoke layer is likely to occur only in close proximity to the fire in rail tunnels, and this layer will then gradually descend to the tunnel floor with increased distance from the fire source.
- Distances between safe locations, i.e., tunnel entrances, emergency exits or safety shelters, may be very long in rail tunnels.
- Emergency exits may be very limited in rail tunnels.
- The rail tunnel environment is unfamiliar to people in general, and is typically never occupied other than onboard trains.
- Natural lighting is absent in rail tunnels, and in case of fire, light levels can be expected to be very low.
- The number of people occupying a rail tunnel at the same time can be very high, as a single train may carry well over a thousand passengers.

These aspects illustrate that rail tunnels introduce a unique set of fire hazards, which have to be specifically considered, both during operation and design. They also illustrate that fire rescue services can face severe problems in case of a rail tunnel fire (Bergqvist, Frantzich, Hasselrot, & Ingason, 2001; Ingason, Bergqvist, Lönnermark, Frantzich, & Hasselrot, 2005). Among other things, there will be only a limited number of exits/entrances available for use. In addition, it is likely that the tunnel will be filled with smoke and that the overview of an accident will be very limited. Consequently, fire rescue services are unlikely to play a lifesaving role during the early stages of a rail tunnel fire, particularly during the time available for a safe escape.

In case of fire, people should be able to evacuate to a safe place or be rescued by other means in case of fire (ISO, 2009, 2011; Proulx, 2008a; SFPE, 2003, 2007). In this perspective, rail tunnels are no different from above-ground buildings. However, as fire rescue services are unlikely to play a life-saving role, people in rail tunnel fires have to adhere to the so-called self-rescue principle. This means that they have to rely on their own ability to evacuate to a safe place, with assistance only from existing technical installations and other people (Kecklund, Petterson, Anderzén, Frantzich, & Nilsson, 2007, p. 30). Consequently, in case of fire evacuation in a rail tunnel, people must first evacuate the train in which they are travelling. Thereafter, they have to evacuate the rail tunnel. During this process, they must overcome a number of obstacles, both mental and physical. This involves making the decision to evacuate, evacuating the train to track level, and finding an appropriate way to safety in an unfamiliar environment. For many people, not the least elderly or people suffering from any form of disability, this can be particularly challenging. Furthermore, it may take significant time, time that may not be available in case of fire.

Evacuation of people in rail tunnel fires is, thus, a highly undesirable event, and may constitute a serious risk to life safety. Therefore, a general rule is to move passenger trains on fire to a safe place, either out of the tunnel or to the nearest station, and there disembark its passengers (Burnett, 1984; European Commission, 2014). This means that the total evacuation time can be significantly reduced, partly by removing a number of difficult obstacles, and partly by reducing the distances to a safe location. However, past reviews of passenger train accidents reveal that emergency evacuations of trains seldom occur when the train is at a platform (Galea, Blackshields, Lawrence, Finney, & Cooney, 2013, p. 1024). In some rail tunnel fires, this has led to severe consequences in terms of lives lost and persons injured.

One of the worst examples of such a rail tunnel fire occurred in Baku, Azerbaijan, on October 28, 1995 (Carvel & Marlair, 2011, p. 14; Frantzich, 2000, p. 14; Fraser-Mitchell & Charters, 2005, pp. 548-549, 551; Martens & Jenssen, 2012, pp. 78, 81; Rohlén & Wahlström, 1996; Shields & Boyce, 2004). During rush hour, an electrical fault caused a fire on a fully packed train in the Baku Metro, which eventually led to a stop in the tunnel between two stations. Smoke rapidly began to fill the cross-section of the tunnel, and a combination of events led to the deaths of almost 300 people. The majority never got out of the train, and those who did faced a severely hostile tunnel environment, which was dimly lit and obscured by toxic smoke.

Another example of a catastrophic rail tunnel fire is the fire in the Kitzsteinhorn funicular tunnel near Kaprun in Austria, which occurred on November 11, 2000 (Bergqvist, 2001; Carvel & Marlair, 2011, p. 12; Fraser-Mitchell & Charters, 2005, pp. 545, 547-548, 551; Larsson, 2004; Martens & Jenssen, 2012, p. 81; Schupfer, 2001). A fire on a funicular train eventually made the train stop 600 meters into the steeply ascending tunnel. Only 12 people who managed to evacuate the train, and who decided to evacuate downward, away from the smoke, survived. The rest, in total 150 people, were killed either in the tunnel above the train or onboard the train.

Together, these and other rail tunnel fires illustrate that rail tunnel evacuation can lead to very severe consequences in terms of lives lost and persons injured. They also illustrate that these types of events do occur, and that a crucial aspect of the safety level of a rail tunnel is the possibility of a safe escape. In order to avoid devastating accidents in the future, it is therefore necessary to consider human behavior aspects both in the design phase and operation of rail tunnels. This requires the ability to understand, and, furthermore, to predict human behavior. For example, how do people behave and react in the event of a rail tunnel evacuation due to fire? And how should a rail tunnel be designed in order to ensure that occupants in that system can leave it or, by other means, be rescued in case of fire?

The answers to these questions are not obvious, as much of the data and information concerning human behavior, by tradition, is based on research related to buildings above ground. In addition, it is sometimes put forward that conceptual theories and models to describe human behavior in buildings above ground are not applicable to underground facilities such as rail tunnels (Canter, Donald, & Chalk, 1992; Shields & Boyce, 2004). However, if design solutions and safety concepts in rail tunnels are to be in line with the likely behavior patterns of the people occupying them, applicable data and information on human behavior in rail tunnel fires are essential. This applies both to rail tunnel owners and operators, who may want to adapt safety concepts to the expected behavior of people, and to designers who may want to evaluate the fire safety design of a rail tunnel by assessing required safe escape times. This requires qualitative information on behavioral aspects as well as quantitative data on, among other things, flow rates and walking speeds of people, also under the impact of smoke.

Research objectives

Although they are rare, rail tunnel fires do occur, and the discussion above demonstrates the catastrophic potential of such an event, particularly when passenger trains cannot transport people to a safe location. In order to reduce the risk to people during a rail tunnel evacuation, and in order to achieve safe rail tunnels in the future, data and information about human behavior in rail tunnel fires are crucial. Unfortunately, this type of information is severely restricted. The objective of this thesis is, therefore, to increase the knowledge on rail tunnel evacuation in case of fire by presenting:

1. A theoretical framework that can facilitate the understanding of human behavior in the event of fire in underground rail transportation systems.
2. Information and data on:
    a. Human behavior and the flow rate of people during train evacuation in rail tunnels.
    b. Human behavior and walking speeds in smoke-free as well as smoke-filled rail tunnels.
3. Recommendations on how technical installations in rail tunnels can be designed so as to improve the safety for occupants in the event of fire.

Publications

The research presented in this thesis is a partial fulfilment of the requirements for a doctoral degree in engineering, and is based on the four appended papers. All papers have been peer-reviewed, accepted, and, furthermore, published in various international scientific journals. Below, references to the four publications are presented together with a description of the author's contribution to the papers. In addition to these four papers, the author has been involved in research related to the topic of the thesis, which has been presented in other publications that are not included as thesis papers. These publications may provide additional valuable information related to rail tunnel evacuation, and are therefore listed below as related publications.

Thesis papers

The four papers of the thesis are:

Paper I	Fridolf, K., Nilsson, D., & Frantzich, H. (2011). Fire Evacuation in Underground Transportation Systems: A Review of Accidents and Empirical Research. *Fire Technology, 49*(2), 451-475. doi: 10.1007/s10694-011-0217-x
Paper II	Fridolf, K., Nilsson, D., & Frantzich, H. (2014). The flow rate of people during train evacuation in rail tunnels: Effects of different train exit configurations. *Safety Science, 62*(C), 515-529. doi: 10.1016/j.ssci.2013.10.008
Paper III	Fridolf, K., Ronchi, E., Nilsson, D., & Frantzich, H. (2013). Movement speed and exit choice in smoke-filled rail tunnels. *Fire Safety Journal, 59*, 8-21. doi: 10.1016/j.firesaf.2013.03.007
Paper IV	Fridolf, K., Nilsson, D., & Frantzich, H. (2015). Evacuation of a Metro Train in an Underground Rail Transportation System: Flow Rate Capacity of Train Exits, Tunnel Walking Speeds and Exit Choice. *Fire Technology*, 1-38. doi: 10.1007/s10694-015-0471-4

In the first paper, Paper I, a review of previously reported fire accidents and of empirical research, e.g., conducted evacuation experiments, is presented. The review of the previously reported accidents is based on a theoretical framework, including four generally accepted theories and models on human behavior in fire. In the subsequent three papers, Paper II-IV, the findings of three different evacuation experiments are described. The author's contribution to the four papers is illustrated in Table 1, which describes an estimate of the degree of responsibility and amount of work that the author has contributed to different parts of the papers. The three levels of engagement are defined accordingly:

Minor	The author has taken minor responsibility and performed a small proportion of the work (less than 1/3 of the responsibility and amount of work)
Medium	The author has taken medium responsibility and performed approximately half of the work (between 1/3 and 2/3 of the responsibility and amount of work)
Major	The author has taken major responsibility and performed a large proportion of the work (more than 2/3 of the responsibility and amount of work)

As can be seen in Table 1, the degree of responsibility and amount of work for each paper was divided into four different steps. The first step, termed planning and preparation, includes the formulation of a research question and a strategy for answering it, i.e., the formulation of one or more research objectives. Depending on the type of study, this may include activities related to experimental design, data collection preparation and, if applicable, the formulation of an application for ethical approval.

The second step, termed execution, includes data collection with the overall goal of enabling robust conclusions. Activities that may be included in this step are: reading literature, performing observations, collecting questionnaires, and performing interviews. In the third step, the material is analyzed and related to the research objective identified in the first step. The analysis may include activities such as: relating the collected data to current knowledge, investigating video recordings, structured analyses of questionnaire and interview answers, and performing statistical analyses. Finally, the fourth step involves the preparation of the paper. In other words, composing and submitting it to a scientific journal for review. The fourth and final step also includes the subsequent revision of the paper based on the reviews by the reviewers.

Table 1. A presentation of the author's contribution to the four different papers.

Step	Degree of responsibility and amount of work			
	Paper I	Paper II	Paper III	Paper IV
1. Planning and preparation	Medium	Major	Medium	Major
2. Execution	Major	Major	Major	Major
3. Analysis	Major	Major	Medium	Major
4. Preparation of paper	Medium	Major	Medium	Major

Related publications

A number of additional publications, which have involved the author, are related to the topic of the thesis. They may therefore provide additional valuable information on rail tunnel evacuation, although they are not included as thesis papers. The related publications of this thesis are (sorted by date of publication):

Publication I	Fridolf, K. (2010). Fire evacuation in underground transportation systems: a review of accidents and empirical research. Lund: Lund University.
Publication II	Grindrod, S., Welch, S., & Fridolf, K. (2011). *A priori modelling of an underground evacuation.* Paper presented at the Advanced Research Workshop: Evacuation and Human Behaviour in Emergency Situations, Santander.
Publication III	Fridolf, K., Nilsson, D., & Frantzich, H. (2012). *Taking advantage of theories and models on human behaviour in the fire safety design of underground transportation systems.* Paper presented at the fifth International Symposium on Tunnel Safety and Security, New York.
Publication IV	Fridolf, K., & Nilsson, D. (2012). A questionnaire study about fire safety in underground rail transportation systems. Lund: Lund University.
Publication V	Fridolf, K., Nilsson, D., & Frantzich, H. (2012). *Train evacuation inside a tunnel: An interview study with senior citizens and people with disabilities*. Paper presented at the fifth International Symposium on Human Behaviour in Fire, Cambridge.
Publication VI	Nilsson, D., Fridolf, K., & Frantzich, H. (2012). *Design of evacuation systems in underground transportation systems*. Paper presented at the fifth International symposium on Human Behaviour in Fire, Cambridge.
Publication VII	Fridolf, K., & Nilsson, D. (2012). WP2 - Evacuation. *The METRO Project: Final report* (pp. 37-44). Mälardalen: Mälardalen University Press.
Publication VIII	Fridolf, K. (2013). Evacuation of a Smoke Filled Tunnel: Human Behaviour, Movement Speed and Exit Choice. Lund: Lund University.
Publication IX	Fridolf, K., & Frantzich, H. (2014). *Evacuation in Underground Rail Transportation Systems: A Summary of the Findings of the METRO Project*. Paper presented at the sixth International Symposium on Tunnel Safety and Security, Marseille.
Publication X	Fridolf, K., Andree, K., Nilsson, D., & Frantzich, H. (2014). The impact of smoke on walking speed. *Fire and Materials, 38*(7), 744-759. doi: 10.1002/Fam.2217
Publication XI	Fridolf, K., & Wahlqvist, J. (2014). Predictive Capabilities of Computer Models for Simulation of Tunnel Fires. Lund: Lund University.

Publication XII	Norén, J., Delin, M., & Fridolf, K. (2014). Ascending Stair Evacuation: What do We Know? *Transportation Research Procedia, 2*(C), 774-782. doi: 10.1016/j.trpro.2014.09.087
Publication XIII	Fridolf, K., & Frantzich, H. (2014). Delrapport: Test av vägledande system i en tunnel. Lund: Lunds universitet.
Publication XIV	Fridolf, K., & Frantzich, H. (2014). *Fire Protection of Underground Transportation Systems: A Decision Support Tool for Designers and Rescue Services*. Paper presented at the SFPE 10th International Conference on Performance-Based Codes and Fire Safety Design Methods, Gold Coast.
Publication XV	Fridolf, K., & Frantzich, H. (2014). TuFT: Tunnel Fire Tools - Teknisk dokumentation. Lund: Lunds universitet.
Publication XVI	Fridolf, K., & Frantzich, H. (2015). Test av vägledande system i en tunnel. Lund: Lunds universitet.
Publication XVII	Fridolf, K., Frantzich, H., Ronchi, E., & Nilsson, D. (2015). *The relationship between obstructed and unobstructed walking speed: Results from an evacuation experiment in a smoke filled tunnel*. Manuscript to be presented at the sixth International Symposium on Human Behaviour in Fire.

Delimitations

A number of delimitations are associated with the material presented in this thesis. It is important to be aware of these, and particularly to consider them in, for example, application and design. They are, therefore, briefly presented below.

Environment

Rail tunnels may be part of larger underground transportation systems. Such systems may, for example, include underground stations and other similar locations where people may reside when not onboard trains in the tunnel. The information presented in this thesis is, however, delimited to the rail tunnel and the evacuation therein. More specifically, it focuses on evacuation of people from a train in a tunnel, and the subsequent evacuation to a safe location. That safe location is not explicitly defined, but may be a tunnel portal, an emergency exit, or possibly an underground station.

People with disabilities

The thesis is delimited to rail tunnel evacuation of able-bodied people. This is, among other things, illustrated by the characteristics of the participants that took part in the evacuation experiments presented in Paper II-IV. Although people as old as 76 years took part in the experiments, people with disabilities were excluded due to ethical issues, mainly the increased risk of injury. People with disabilities, and their abilities during rail tunnel evacuation have, however, to some extent been addressed in other studies published in publications related to this thesis, see Fridolf, Nilsson, and Frantzich (2012).

Fire

There may be many causes that require for passengers to be evacuated from a train in a rail tunnel. This thesis is, however, focused on rail tunnel evacuation due to fire. Still, the fire itself is only considered as a background factor, and is not explicitly studied in relation to the evacuation. Consequently, information such as the position, the rate of growth or the size of the fire, is not discussed. A fire may, for example, occur on a passenger train that needs to be evacuated, in a maintenance area in the tunnel, or in a location connected to the rail tunnel, such as an underground station. It is acknowledged that such aspects may have an effect on the specific response of people during an evacuation. However, such investigations have not been done. Thus, in this thesis, the fire is to be interpreted merely as an initiator of the evacuation.

Engineering perspective

Research on evacuation and human behavior in fire typically emphasizes the interplay between people, the built environment, and the fire. Thus, it is recognized that the research field has strong links to psychology. The material presented in this thesis is, however, mainly written from an engineering perspective. This means that it tends to describe the behavior of people during rail tunnel evacuation both qualitatively and quantitatively, and not the physiological and psychological processes generating those behaviors.

Outline

This chapter provided background information on rail tunnel evacuation, and introduced the four papers included in the thesis. In the next chapter (Method), a number of research methods and data collection techniques commonly used in research related to human behavior in fire in general, and in this thesis in particular, are introduced. The introduction to the research methods and data collection techniques forms a basis for the discussion in the subsequent chapter (Research strategy) which introduces and discusses the research strategy that was selected to generate new knowledge on rail tunnel evacuation.

The next three chapters summarize the results presented in Paper I-IV. Firstly, a theoretical framework is introduced (A theoretical framework), which can facilitate the understanding of human behavior in the event of fire in underground rail transportation systems. Based on the findings in Paper I, four theories and models are presented, and their applicability to evacuation in underground transportation systems is discussed. Secondly, data and information related to train evacuation in rail tunnels are presented (Train evacuation). The chapter begins with a description of the most important findings of previously conducted empirical studies, and is followed by a summary of the findings of Paper II and IV. Thirdly, data and information related to rail tunnel evacuation are presented (Tunnel evacuation). The content is divided into two factors: movement in the tunnel and exit choice. As in the chapter on train evacuation in rail tunnels, the chapter on tunnel evacuation begins with a description of the most important findings of previously conducted empirical studies, and this is then followed by a summary of the findings presented in Paper III and IV.

Following the summary of the results, the next chapter (Application and design) focuses on how the information and data presented in this thesis can be used in application and design. Examples are given of how accident investigators, fire safety designers, and owners and operators of rail tunnels can use the material in their respective fields. Finally, the following two chapters present the most important conclusions of this thesis (Conclusions), as well as suggestions for future research (Future research).

Method

Science is about investigating the world and interpreting what is seen (Andersson, 2012, p. 13). It is intimately associated with a number of research methods and data collection techniques, and a sensible selection of which methods and techniques to use to address a particular problem, i.e., the choice of the research strategy to use, is essential for maintaining a high degree of scientificity (Ejvegård, 2009, p. 33). In this thesis, a clear distinction is made between a research method and a data collection technique. This is, however, not always the case, and sometimes different data collection techniques are considered as part of the research method, see the book by Holme and Solvang (1997). Therefore, the two terms are defined in Table 2, inspired by the definitions proposed by Ejvegård (2009, p. 33):

Table 2. The differences between a research method and data collection technique.

Term	Definition
Research method	A research method is a scientific approach to the topic of interest, and how it will be treated.
Data collection technique	A data collection technique is a procedure to collect information in order to describe, compare, formulate hypotheses, explain or predict something.

The choice of research method, as well as data collection technique, should be dictated by the research problem, and the type of question that the researcher strives to answer (Dahmström, 2011, p. 21; Yin, 2009, p. 8). Each method and technique does, however, bring with it both advantages and disadvantages, and it can therefore be beneficial to combine research methods as well as data collection techniques in a research study (Ejvegård, 2009, p. 34; Holme & Solvang, 1997, p. 85; Robson, 2011, pp. 166-167; Yin, 2009, pp. 114-118). Adopting more than one data collection technique may, for example, help explain observations made in a study, which can be particularly important when unanticipated or unusual findings emerge. Another potential benefit of combining research methods and data collection techniques is that it may enhance the validity of research findings.

Validity is a term often used together with reliability when judging the quality of research (Ejvegård, 2009, pp. 77-82; Yin, 2009, pp. 40-45), also in research on human behavior in fire. The literature on research methodology offers a wide variety of definitions for these terms, but in general, validity relates to accuracy, whereas reliability relates to reproducibility (Robson, 2011, pp. 77, 85). More detailed descriptions of the terms validity and reliability are, however, also available. Environmental psychology researchers are, for example, fond of dividing validity into internal validity and external validity (Bellamy & Geyer, 1990, pp. 10-11). Yin (2009, pp. 40-45), furthermore, adds an additional part to validity termed construct validity. Thus, interpretation of the term validity may be ambiguous, and in order to avoid misinterpretations when discussing the quality of the research presented in this thesis, the definitions in Table 3 are used (Yin, 2009, p. 40):

Table 3. The differences between construct, internal and external validity, and reliability.

Term	Definition
Construct validity	The extent to which correct operational measures are used for the concepts being studied.
Internal validity	The extent to which causal relationships are identified.
External validity	The extent to which the findings of a study can be generalized to a specific domain.
Reliability	The extent to which the operations of a study can be repeated with the same results.

Different data collection techniques may yield either qualitative data or quantitative data, and depending on the type of data, validity and reliability may be expressed and measured differently. Still, similar tactics can be used to increase the validity and reliability of both qualitative and quantitative studies. As an example, multiple sources of evidence, i.e., data collection techniques, may be used to increase the construct validity of a study (Robson, 2011, p. 87; Yin, 2009, pp. 41-42). The type of tactic, and when to apply it in the research process, depend on the type of criteria being addressed. For example, in order to increase construct validity and reliability, a number of choices must be made during the data collection phase. In contrast, internal validity is affected by how the data analysis is executed and external validity by modifications to the research design.

In the following parts of this chapter, a number of research methods and data collection techniques commonly used in research related to human behavior in fire in general, and in this thesis in particular, are introduced. The presentation is brief, and no comprehensive theoretical or practical descriptions are provided. Rather, the introduction to the research methods and data collection techniques is intended to form a basis for the discussion in the following chapter on the selected research strategy, i.e., the combination of research methods and data collection techniques employed in order to generate new knowledge on rail tunnel evacuation.

Research methods

The purpose of conducting research is to explore, describe and/or to explain a particular phenomenon in the world, and research questions are typically categorized as *who*, *what*, *where*, *how* and *why* questions (Robson, 2011, p. 39; Yin, 2009, pp. 7-14). In general, the type of research question can be used to evaluate when to use a particular research method. However, aspects such as the required control of behavioral events, and whether or not the research is focused on contemporary or historical events, are also influential.

Two research methods often used in research on evacuation and human behavior in fire are: case studies and experiments. These are methods particularly relevant when answers to *how* and *why* questions are sought, and when contemporary events are of interest (Yin, 2009, p. 8). In other words, the research methods may be used to provide descriptive and explanatory knowledge. In this regard, it shares many similarities with research in environmental psychology (Bell, Greene, Fisher, & Baum, 2001, p. 7), which is a field that also advocates case studies and experiments as research methods.

The main difference between case studies and experiments relates to the manipulation of the setting. In a case study, the behavior of interest is not manipulated as opposed to an experiment in which the researcher manipulates the setting in order to affect the behavior. However, a number of other differences exist as well, and the two research methods do bring with them a number of advantages and disadvantages. Therefore, they are briefly presented below.

Case studies

As the term suggests, the case study research method emanates from a specific case which is studied in detail, often with the aim of describing something in the real world (Ejvegård, 2009, p. 35). It is most often used to generate qualitative data, but case studies may also be used to generate quantitative data (Robson, 2011, p. 136; Yin, 2009, pp. 132-133). A technical definition of the case study research method has been proposed by Yin (2009, p. 18), and the first part of that definition is quoted below:

> A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context […]

The second part of the definition covers three additional aspects. One of these, which is deemed particularly important, states that the case study research method relies on multiple sources of evidence in which data needs to converge in a triangulating fashion.

The advantages of using a case study research method to investigate a particular phenomenon are many. One of the strengths of the method is its ability to use and combine multiple sources of information such as documents, observations and interviews. Another is that, in contrast to experiments, it allows a researcher to initially explore a case before formulating specific research questions or hypotheses to be addressed (Ejvegård, 2009, p. 36). In addition, the case study research method allows the researcher to study many variables related to the object (the case) simultaneously as opposed to an experiment in which many objects, but only a few variables, may be considered at the same time.

A number of disadvantages have, however, been raised by the research community (Robson, 2011, pp. 135-137; Yin, 2009, pp. 14-15). One of the main criticisms raised about case studies is that they provide little basis for generalization of the results. Consequently, some argue that the external validity of case studies is low. Another frequently occurring concern about case studies is that they cannot prove causal relationships, i.e., that generated results lack internal validity. In fact, some researchers argue that testing hypotheses by experiments is the only way to provide explanatory knowledge (Andersson, 2012, pp. 85-88). This is claimed to be due to difficulties in isolating confounding parameters. Finally, a third concern about case studies relates to the lack of objectivity, i.e., that research results will always be more or less affected by the researcher, suggesting that the reliability is low. Most of these concerns are, however, addressed as prejudices by Yin (2009, p. 16). The problem, as he sees it, is rather, that case studies are difficult to conduct, and that the lack of formally defined skills for performing good case studies is the reason behind many of the above-mentioned points of criticism.

Within the field of research on human behavior in fire situations, case studies may be used to study the human behavior in past fire accidents. Such case studies allow the question, *how*, to be addressed, partly by including observations and witness statements related to the evacuation related to the fire. In other words, the case study research method may provide descriptive knowledge which stems from real-life environments, something which may be difficult to re-create in an experiment. Such summaries have been done by, for example, Wood (1972) and Bryan (1977), who, by studying numerous fire incidents, formulated conclusions about typical activities and behaviors undertaken by fire victims in building fires.

The case study research method has also been demonstrated to provide explanatory knowledge within the field of research on human behavior in fire. As an example, Canter, Breaux, and Sime (1980) developed a general and well-known behavior sequence model of human behavior in fires, which is presented later in this thesis. The model stems from multiple case studies of domestic, hospital and multiple occupancy fires in which characteristic behaviors in each occupancy type were condensed into a general model based on findings from each occupancy type.

Experiments

In contrast to the use of case studies, performing experiments aims at interfering with the world. The experiment research method is used to study a change in something, and the effects that this change may have on something else (Andersson, 2012, pp. 83-85; Bell et al., 2001, pp. 10-12; Montgomery, 2013, p. 1; Robson, 2011, p. 94). An attempt to define the experiment research method is presented by Andersson (2012, p. 83), who states that:

> […] an experiment involves a strategic manipulation of a system to create an organized response […]

In this definition, the manipulation of a system refers to the manipulation of one or more (independent) variables to study the response in another (dependent) variable.

Often, experimental studies are discussed in contrast to strictly observational studies, i.e., case studies (Andersson, 2012, pp. 83-88). Montgomery (2013, p. 1), for example, states that whereas observing a system in operation is essential to understanding and learning about how the system works, the execution of an experiment is necessary in order to understand cause-and-effect relationships in that system, i.e., to prove that a variation in one variable is the actual cause of the variation in another. This opinion is also shared by Andersson (2012, p. 87), who advocates that a case study, as defined in this thesis, may only reveal correlations between variables, which does not necessarily mean that the change to one variable causes the change in the other. However, as pointed out above, this strict view of experiments as the only research method that can provide explanatory knowledge and support for causation, is not shared by everyone.

Experiments are typically divided into two categories. These include laboratory experiments, which are performed in laboratory settings, and field experiments, which are performed in natural settings (Bell et al., 2001, pp. 10-12; Robson, 2011, pp. 93-104). Regardless of type, experiments are most often used as a research method to gain quantitative data. However, experiments may very well also be used to collect qualitative information, and often quantitative and qualitative data are produced simultaneously. This is particularly true for research in the field of evacuation and human behavior in fire when evacuation experiments involving human participants are conducted.

As Nilsson (2009, pp. 17-18) points out, the distinction between a laboratory experiment and a field experiment is not always clear. This is because there are different views on what defines a laboratory or a natural setting, and on which basis such a categorization should be made. However, in this thesis, a field experiment is defined as an experiment that is performed in a natural environment which the participants could encounter during every day routines. In contrast, a laboratory experiment is defined as an experiment that is performed in a controlled environment, which the participants do not encounter during every day routines.

In general, laboratory experiments offer a high level of control of the variables of interest. However, results from a laboratory experiment may be more difficult to generalize to a real-life setting than results collected in a field experiment. A field experiment does, on the other hand, offer less control especially over independent variables that may affect the dependent variable. Consequently, a laboratory experiment may provide research findings with high internal validity, but low external validity. The situation is reversed for a field experiment. One strategy to compensate for this in both types of experiments is to combine different data collection techniques (Robson, 2011, pp. 161-174). This could, furthermore, improve other aspects related to the quality of the research, such as construct validity.

It is acknowledged that the type of definitions used to categorize experiments in this thesis do not take into account, for example, information given to participants prior to an experiment. Such information is still likely to affect a participants' perception of an experiment setting. In addition, there are other aspects that may be used to classify an experiment, which can also impact the quality of the data generated. As an example, a field experiment in which only young and healthy students take part is likely to lack external validity as the findings are difficult to generalize to a broader population. Therefore, although the experiments in this thesis are termed as laboratory or field evacuation experiments, it is necessary to examine other aspects also when reviewing the quality of the findings. This becomes particularly clear when, for example, a comparison is made between the laboratory experiment presented in Paper II and the laboratory experiment presented in Paper III.

Data collection techniques

In addition to defining an objective of the research and selecting an appropriate research method, it is necessary to make a decision on how to collect the information of interest (Robson, 2011, p. 235). As in the selection of a research method, the data collection technique should be dictated by the purpose of the research, i.e., whether it is being performed in order to explore, describe, compare, explain, or predict something. Furthermore, the choice of data collection technique depends on whether qualitative or quantitative data are of interest, or if a combination of the two is desirable.

In research on evacuation and human behavior in fire, typically three data collection techniques are used. In this thesis, they are defined as questionnaires, interviews and observation. The latter is not to be confused with an observational research method, i.e., a case study. Instead, observation as a data collection technique in this thesis simply relates to the observations that are made during the execution of a research study. This is independent of whether those observations are made simultaneously as the experiment takes place, or in retrospect by studying, for example, video recordings. The three different techniques are briefly presented below.

Interviews

Collecting data in interviews is common within social sciences, and typically, a distinction is made between structured, semi-structured, and unstructured interviews (Dahmström, 2011, pp. 98-106; Ejvegård, 2009, pp. 51-55; Holme & Solvang, 1997, pp. 99-109; Robson, 2011, pp. 278-301; Yin, 2009, pp. 106-109). A common characteristic, however, is that all interviews include someone (in this case a researcher) asking questions, and one or more people answering those questions (Robson, 2011, p. 278). Interviews are typically used to collect qualitative data, and may be stand-alone features of a research study, or a complement to other data collection techniques. In particular, interviews are frequently used as an important source of information within the case study research method (Yin, 2009, p. 106).

Variations of all three interview types exist, but in general, a structured interview means that the researcher has prepared a number of questions prior to the interview and has decided the order in which they will appear during the interview (Robson, 2011, pp. 279-280). In a semi-structured interview, a number of questions have also been prepared by the researcher prior to the interview. However, the semi-structured interview can be described as more flexible, which means that the prepared list of questions serves more as a guide to the researcher. Default wording of the questions, and the order in which the questions are asked, are dictated by the flow of the interview and are, thus, greatly dependent on the respondent. Finally, the unstructured interview emanates from the area of interest to the researcher, but questions and the order in which they will appear during the interview are not decided upon.

Interviews represent a common data collection technique used in the research field of human behavior in fire. There are examples of cases when interviews have been used as the sole data collection technique, as well as when interviews have been used to complement other data collection techniques. Extensive analysis of the evacuation of the World Trade Center Towers on September 11, 2001, for example, has been conducted by collecting data in telephone and face-to-face interviews (Averill, Peacock, & Kuligowski, 2012). An example of when interviews have been used as a complement to observations in an experiment is related to human behavior and tenability due to fire smoke (Jin, 1997).

The main advantage of the interview as a data collection technique is that it offers a possibility to follow up on answers given by respondents, and to provide a dimension to the understanding of a research question not necessarily captured by, for example, a questionnaire study (Ejvegård, 2009, p. 63; Robson, 2011, pp. 280-281; Yin, 2009, pp. 108-109). Interviews, however, are often very time-consuming, and have also been criticized to for their lack of a standardized procedure. This, and the fact that different researchers may probe different respondent answers, simply by asking questions differently or by unconscious use of non-verbal cues, implies that the reliability of interviews is low. Instructions on how to minimize the risk of bias, however, are provided in the literature, both in terms of general advice as well as a listing of typical questions to avoid during an interview (Foddy, 1993; Robson, 2011).

Questionnaires

Questionnaires share many similarities with interviews, and taken to its extreme, a very structured interview is more or less identical to a questionnaire, with the exception that the questions are read out loud by the researcher (Robson, 2011, p. 278). In a questionnaire, however, the questions are available for the respondent to read on paper and answer in writing. Questionnaires may be distributed in various ways, e.g., by mail, through the Internet, or to respondents at a specific location (Dahmström, 2011, pp. 84-97). When case studies are used as a research method, the former two alternatives are more common. However, in an experiment, questionnaires may be distributed to participants at the location of the experiment.

The questions in a questionnaire are typically either closed-ended or open-ended (Ejvegård, 2009, pp. 55-63; Robson, 2011, pp. 236-277). Closed-ended questions are represented by questions that provide the respondent with a number of fixed alternatives. The respondent may be asked either to tick one of the alternatives in so-called multiple choice questions, or one or more of the alternatives in so-called tick box questions. In contrast, open-ended questions allow the respondent to answer the question freely in his/her own words. Thus, open-ended questions may be preferable as they allow the respondent to answer a question without being influenced by the researcher. Furthermore, open-ended questions often offer more nuanced answers compared to closed-ended questions. However, respondents may feel a resistance to answer especially sensitive questions in free text, and may also feel the lack of time or interest in answering such a question. Therefore, closed-ended questions may be preferable in some situations. In addition, closed-ended questions are easier to code and to analyze than answers to open-ended questions.

Questionnaires are often used to complement other data collection techniques in the research field of human behavior in fire. One reason for this, as pointed out by Shields and Boyce (2000, p. 26), is that questionnaires alone may not be sufficient to reveal aspects such as non-escape behaviors. Typically, questionnaires are therefore included in experiments to provide explanatory support to observations of human behavior. This can be illustrated, for example, by a study in which the effectiveness of photo-luminescent way guidance systems were examined (Proulx, Kyle, & Creak, 2000). However, examples do exist where questionnaires have been the only data collection technique. Such an example is a case study by Bryan (1983), who based on replies from 554 survivors, reviewed the human behavior in the fire at the MGM Grand Hotel in November 21, 1980.

In contrast to interviews, questionnaires are less time-consuming and often less costly to use as a data collection technique (Ejvegård, 2009, p. 63; Robson, 2011, pp. 239-240). In addition, researcher bias during an interview can be avoided in a questionnaire, but a drawback is the inability to follow up on an answer provided by the respondent. Answers will also inherently be affected by the respondent's specific characteristics, such as past experience and personality. Furthermore, answers may not always report true beliefs or attitudes, but rather answers that are thought of as desired in the context of the study. Another problem may be a so-called self-enhancement effect, which means that the majority of people in a group of respondents tend to judge their ability to do something as higher than the average respondent in the same group. This has, for example, been exemplified in a study on driving safety (Svenson, 1981). The drawbacks mentioned above can, however, also be anticipated during interviews. Consequently, there are threats to validity in both data collection techniques.

In general, questionnaires are preferable compared to interviews in terms of reliability, as presenting an identical questionnaire to a well-defined sample of respondents produces a high level of reliability (Robson, 2011, pp. 239-240). If the questions are well formulated and unambiguous, it is also likely that valid information will be obtained about, for example, the respondent's beliefs. In other words, well formulated questions in a questionnaire are likely to increase both the construct and internal validity. However, especially when using questionnaires as a complementary data collection technique in an experiment, a potential problem relates to the generalizability of the results. In other words, the external validity may be affected by the potential lack of a representative group of respondents. Another problem related to external validity is the extent to which answers given in a questionnaire conform to real-life actions. The latter is a question of research design, whereas the former, to a large extent, can be addressed by, for example, using checklists to help avoid problems in formulating questions. Here again, many of these problematic aspects are similar to those in the interview.

Although some of the points addressed above are common to many research fields, each field also brings with it a number of unique aspects that need to be considered in an evaluation of reliability and validity. For example, if questionnaires are used to evaluate the behavior among survivors of a past fire, memory is a likely parameter that will affect the respondent's answers, and ultimately, the extent to which conclusions can be drawn. Thus, it is recommended that evaluation of the quality of a research study be made with these unique aspects in mind.

Observation

In this thesis, observation is considered as a data collection technique by which researchers observe others and report on, among other things, their behavior, interactions and/or positions in a given setting (Bell et al., 2001, pp. 16-17; Yin, 2009, pp. 109-113). This setting may either be an environment, which is manipulated by the researcher, or an environment in which no active interaction takes place with the system under study. Consequently, observation is a data-collection technique, which can be used either when the case study research method is adopted, or when the experiment research method is used.

Observation as a data collection technique may vary depending on the question being addressed. Ad-hoc data collection from observation may, for example, be used initially in a research study to reveal potential areas of interest to examine in greater detail. However, observation may also be more formal and may include coding forms, study protocols or other similar observational instruments. Furthermore, observation may be used both during the execution of a research study, as well as after the study has ended. In that case, recording devices such as video cameras may be used to collect and store the information.

In contrast to interviews and questionnaires, the advantage of observation is that it allows for behaviors, actions, and interactions to be measured without having to rely on an individual's ability to formulate feelings, or remembering times and positions in a certain event (Bell et al., 2001, p. 16). In the field of human behavior, this is especially beneficial during experiments in which the participants are initially unaware that they are taking part in an experiment, i.e., unannounced evacuation experiments, or evacuation experiments in which they have received partial, or even misleading, information about the purpose of the experiment. Furthermore, observation from surveillance cameras may add great value to interviews of fire victims in case studies of past fire incidents.

When evacuation experiments are conducted, observation is a data collection technique which is very popular to use. Although it is not as common in case studies, good examples still exist of the use of the technique. One example of this is described by Norén and Winér (2003), who collected information about disembarking passengers from trains during normal operations at a number of train stations. The purpose was to provide empirical data which could be used to describe crowd evacuation in rail tunnels.

Often, video recording equipment is used to record events in a research study (Bell et al., 2001, pp. 16-17; Yin, 2009, pp. 109-113). This enables the data to be studied, i.e., observed, many times, which may reduce subjective judgments, and thus increase the construct validity of a study. It also enables more than one researcher to analyze the material, which may reduce uncertainties and, furthermore, increase the internal validity as it increases the chances of causal relationships to be identified. Having more than one researcher analyzing the same material also increases the reliability of the conclusions drawn. In addition, observation may also capture aspects in a research study which simply are not possible to gather from interviews and questionnaires. Furthermore, it can do so with a high level of precision.

Observation as a data collection technique is, however, also associated with a number of disadvantages (Bell et al., 2001, pp. 16-17; Yin, 2009, pp. 109-113). Typically, subjectivity and human error are mentioned as disadvantages. In addition, the inability to observe all the activity within a setting, and to make out in detail what is really happening, are also often mentioned as drawbacks of observation. These and other disadvantages are strongly related to the coding of the information observed, such as the behaviors undertaken by participants in an evacuation experiment. It may be questioned, for example, if a researcher, by observing a behavior, is always capable of interpreting it correctly.

Research strategy

In the previous chapter, it was concluded that a sensible selection of a research strategy, i.e., combination of research methods and data collection techniques, is essential in order to maintain a high degree of scientificity when conducting research. The presentation of the different research methods and data collection techniques also revealed that each method and technique embraces both advantages and disadvantages that evidently will have an effect on the knowledge that is generated in research studies. In this chapter, the selected research strategy for generating new knowledge on human behavior in rail tunnel fires is, therefore, presented together with a description of the motives behind them. It should be noted that the exact strategy was not decided upon initially, but instead, was partially developed after an initial literature review.

The first step of the research strategy, which is summarized in Figure 2, therefore included a rigorous search and review of literature related to evacuation, human behavior in fire, and life safety in underground transportation systems. Thus, the review covered not only tunnels, but the entire system of which tunnels are a part. During the review, a case study methodology was adopted. This led to the identification of a theoretical framework which was suggested to form a basis for understanding human behavior in the event of fire in underground transportation systems. The literature review also revealed areas on which future research should focus, and this allowed the subsequent steps of the research strategy to be defined.

The focus of the second step of the research strategy was to generate new knowledge related to fire evacuation in rail tunnels. Therefore, two laboratory evacuation experiments were conducted. Finally, in the third step of the research strategy, some of the derived results in the second step were verified, and additional knowledge was generated in a field evacuation experiment.

Ultimately, the research strategy was selected as it was judged to best address the research objectives presented above. In particular, the selection was made to explore the field of rail tunnel evacuation, and to generate descriptive knowledge of high quality. The goal was not to provide causal relationships, but rather to present findings and correlations that could be used to describe different aspects of a rail tunnel evacuation. Still, different strategies were adopted in order to provide support for explanatory knowledge. As an example, participants that took part in the evacuation experiments presented in Paper III-IV were given the opportunity to explain their behavior during their evacuations both in questionnaire and interview studies.

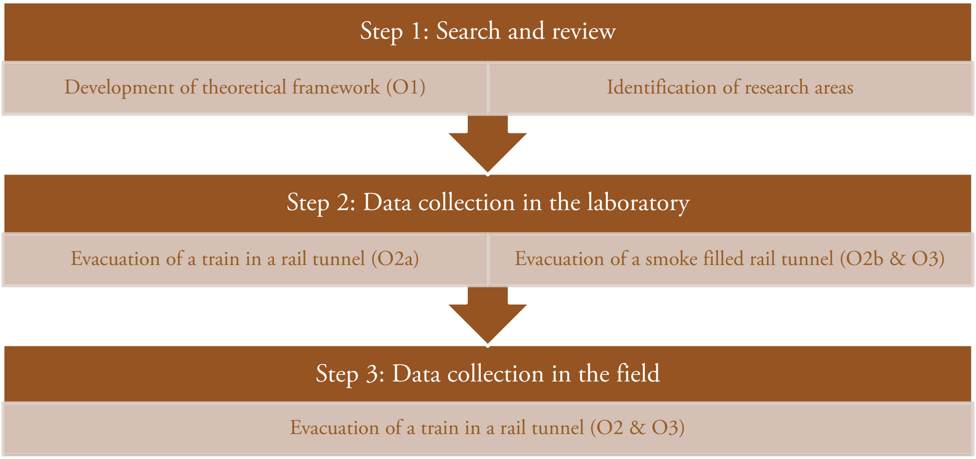

Figure 2. The research strategy adopted for this thesis. O1-O3 refers to the objectives of the thesis (presented above).

The different steps of the research strategy are described in detail below. This includes a description of the research methods adopted, and the data collection techniques used in each of the steps. The presentation is complemented by a brief discussion of ethics as both the laboratory and field evacuation experiments involved human participants.

Step 1: Search and review

The purpose of the first step was to facilitate the understanding of human behavior in the event of fire in underground transportation systems, and to reveal areas on which future research should focus. The review included literature on existing theories and models of human behavior in building fires, as well as past fires in underground transportation systems and empirical research carried out in these or similar settings. The past fire accidents were then reviewed based on a number of identified theories and models. Consequently, a case study methodology was adopted in which multiple cases, i.e., past fires, were reviewed based on a number of pre-existing theories and models.

The strategy allowed the applicability of existing theories and models to be tested, as well as allowing problems related to evacuation in underground transportation systems to be revealed. In addition, previously conducted empirical research could be summarized in order to identify patterns in previous findings, and to expose additional gaps in knowledge related to the topic. The result of the review is presented in Paper I. It should be noted that the paper is based on a technical report published by the author (Fridolf, 2010), in which additional information gathered in the literature review is presented.

The intention of the review was not to solely present all the available literature within the field. It was rather to review the existing knowledge within the field, and at the same time to expand this knowledge by testing the applicability of already existing theories and models of human behavior in fire. In order to guarantee the quality of this review, a structured method to guide the search and review of the literature was developed; see Figure 3 (Ejvegård, 2009, p. 75).

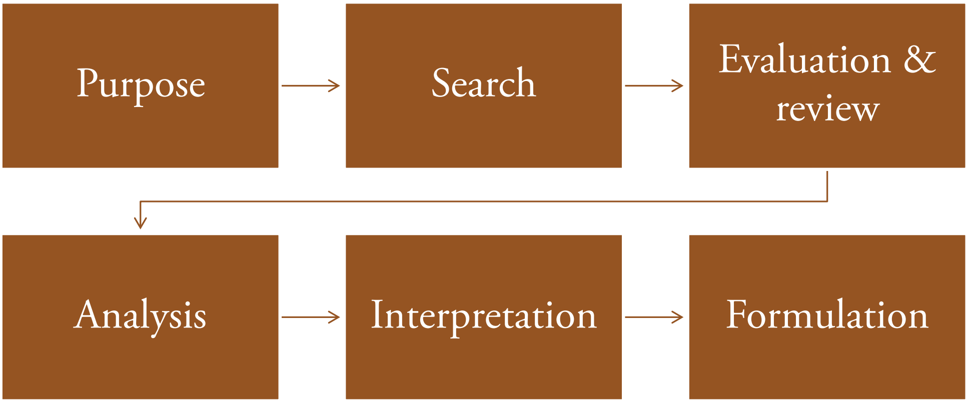

Figure 3. The search and review of literature was guided by the purpose of the literature review.

As can be seen in Figure 3, the search for literature began after the purpose of the review had been defined. The search was initiated by the identification of a number of keywords, and was initially done using electronic databases. One problem with electronic databases is, however, that they differ in their capacity to retrieve material. In order to avoid excluding literature not characterized by the initially defined keywords, other sources of information were, therefore, also used. As an example, the reference lists of the initially retrieved literature were used as one source of further information within the field. Another source of information was hardcopy books, as well as proceedings from fire- and life-safety-related symposia. These were systematically studied in order to find literature not covered by the electronic databases.

Another problematic aspect of the search for literature was that reports of past fire accidents are not typically published as scientific literature. Consequently, the material could not be easily found by performing searches in electronic databases. Instead, a different strategy was adopted, in which a thorough investigation of when and where past fire incidents in underground transportation systems had occurred. Based on this initial compilation, investigation reports and other related publications on these incidents were collected.

After the literature had been retrieved, it was evaluated and reviewed. Each piece of the literature was characterized based on which of the review purposes it related to, and if it had connections to any of the other collected literature. The evaluation also included an evaluation of the assumptions, limitations, reliability, validity, consistency, implications and logical precision of the literature. Literature deemed not relevant was removed, and thereafter, the analysis of the material was initiated.

During the analysis, the theoretical framework was identified. The framework was then used in the review of a number of past fire incidents in underground transportation systems. Furthermore, previous empirical studies were compared and characterized in order to identify the state of knowledge within the field. Finally, the retrieved information and conducted analyses were interpreted and formulated to text. Explanations as to why the theoretical framework was deemed appropriate were sought and explained. Furthermore, findings of past fires were combined with findings of the previously conducted empirical research in order to establish future areas for research.

In total, four theories and models were included in the theoretical framework. The selected theories and models were chosen because their applicability to a number of varying building types had been demonstrated in the past. Thus, the likelihood of them being applicable to underground transportation systems also was deemed to be high. In addition, previous analyses of human behavior both in fire accidents and conducted empirical studies in the context of underground transportation systems indicated that they were applicable to these settings. The selected theories and models were also included in the theoretical framework due to their relative simplicity, and the fact that they were believed to be easily comprehensible.

During the literature search and review, additional theories and models of human behavior in fire were discovered which were not included in the framework. The reason was typically that they were rather conceptual or that they had not been validated other than in theory. Another reason was that the identified theories and models, part of the theoretical framework proposed in Paper I, in some occasions overlapped other existing models and theories. With this in mind, it should be noted that the theoretical framework cannot be said to be complete. However, it consists of four relatively basic, simple and well known theories and models that can provide guidance when trying to understand the behavior of people in fires, also in underground transportation systems.

As with any research activity, the quality of the work in Paper I can be reviewed in terms of validity and reliability. In this perspective, the selection of a structured process to collect, review and analyze the literature is likely to have increased the reliability of the result. Naturally, a review is, by definition, characterized by subjective thoughts and opinions, which affect, especially, the analysis and interpretation of the identified material. However, by adopting a structured process for doing so, the thought process becomes transparent, and it is more likely that the review can be repeated with similar results also by others.

In summary, the review can be divided into two parts. The first part focused on the identification of an appropriate theoretical framework to aid the understanding of human behavior in the event of fire. The second part focused on summarizing and reviewing the different sources of information, and on identifying future research areas. A discussion of validity is therefore presented for the different parts separately.

In order to increase the construct validity of the case study, the review of past fires was based on multiple sources of evidence. This included investigation reports, newspaper articles, and interviews with survivors. Together, these documents allowed the chain of events to be identified. The identification of these events was facilitated by the adoption of the theoretical framework. It is likely that the strategy of basing the review of past fires on already existing theories and models increased the probability of identifying similar patterns in the different fires. Furthermore, the adoption of the framework facilitated explanations of the identified behaviors, which likely increased the internal validity of the case study.

A potential problem in terms of external validity is that only major fires were included in the analysis. This is because major fires are more likely to be analyzed in retrospect and to result in investigation reports. Although these fires provide valuable information, small fire incidents do as well. But in contrast to major incidents, which can provide valuable information on what went wrong, observations from minor incidents are likely to reveal what went right. It is acknowledged that behaviors in minor incidents may vary from that in major fires, and if so, that these variations are not captured in the analysis. Still, the theoretical framework may provide a basis for understanding and discussing human behavior in general, rather than the exact behavioral pattern of each individual in minor incidents also.

For the second part of the literature review, which was focused on identifying future research areas, the quality of the conclusions is strongly interlinked to the quality of the literature included in the review. Thus, in some perspectives, the validity of the review is reflected in the validity of the included literature. A structured method was, therefore, adopted in order to include studies of high quality in the review. In addition, many different sources of information were combined in order to ensure valid conclusions. Furthermore, these numerous sources of information were combined to reveal similar patterns between, for example, different empirical studies. Together, this is likely to have increased the probability that future areas of research were correctly identified.

The literature review identified a number of areas, which were deemed particularly important in terms of a successful fire evacuation in underground rail transportation systems. These areas related to:

1. Information to direct people to safe locations, i.e., to aid way-finding.
2. Bottlenecks that could result in flow constraints, for example, the vertical distance between the train and the tunnel floor.
3. The movement of people, especially the speed with which people travel.

When previous empirical research was reviewed and summarized, it became obvious that data related to these aspects were scarce. In addition, the past fires that had been reviewed also illustrated the need for more information on the topics.

Step 2: Data collection in the laboratory

In the second step of the research strategy, data related to the above-mentioned areas were collected. The data collection was made in two laboratory evacuation experiments, the first of which focused on the evacuation of a train in a rail tunnel, and the second, on the evacuation of a rail tunnel filled with smoke.

Experiment 1: Evacuation of a train in a rail tunnel

The objective of the first experiment was to explore and describe the potential effects of various train exit configurations on the flow rate of people during an evacuation of a train in a rail tunnel. Furthermore, the experiment was aimed at qualitatively investigating other related aspects that could affect the flow, for example, interactions between people. The study is presented in Paper II, and was complemented with an interview study in which elderly and senior citizens were interviewed about their perceived ability to evacuate a train in a tunnel (Fridolf et al., 2012).

The reason why the study was conducted as an experiment was the interest in how the flow rate of people would be affected when the train exit was manipulated. In total, the experiment involved 18 different evacuation scenarios, i.e., scenarios in which the train exit configurations were modified, and two groups of participants took part in nine scenarios each. More specifically, 46 participants took part in the first nine scenarios, and 38 participants took part in the latter nine scenarios. Furthermore, each scenario was run for approximately 5 minutes, which means that each participant evacuated the train more than once in every scenario.

The participants were recruited among students at the Faculty of Engineering, Lund University, and due to this, they represented a relatively young and healthy sample of participants. Prior to the experiment, the participants received some information about the experiment, i.e., that it would involve the evacuation of a train in a tunnel. The information, however, did not include any details on the variations between each scenario.

The decision to perform the experiment in a laboratory was taken mainly because it offered a high level of control of the variables of interest. For example, the train exit could be easily modified and tested. Furthermore, other variables not of interest could be controlled and held constant. This meant, for example, that constant queues inside the train could be arranged in order to enable measurements of the flow rate of people through the train exit during congestion.

A model of a train was used in the experiment. As can be seen in Figure 4, the lateral space between the train and the tunnel wall was limited to 0.85 m. The design of the rig was based on a typical commuter train used by Stockholm Public Transport, and was furnished accordingly. In total, the length of the rig was 6.1 m, hence shorter than a real train. However, the length was enough to fit a set of three train seats on each side of the train exit, and for people to queue inside the train before reaching the train lobby.

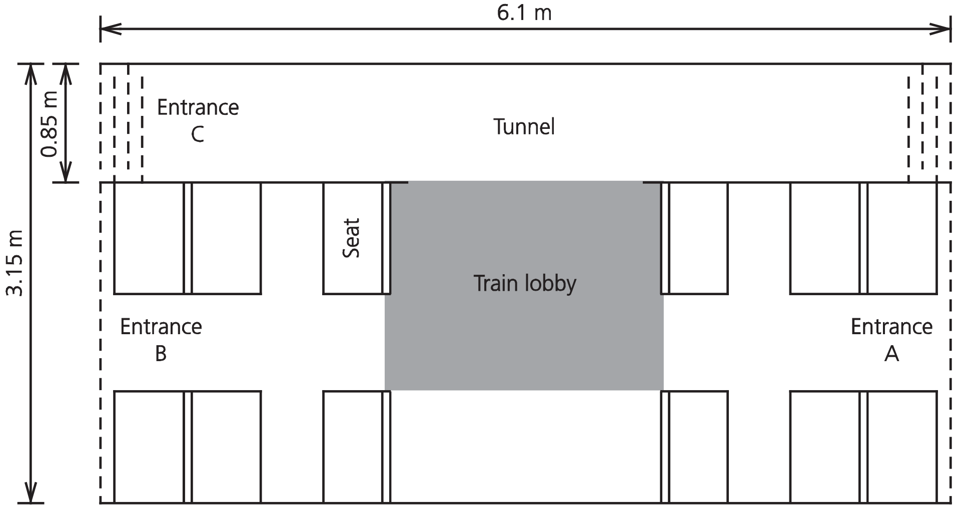

Figure 4. Illustration of the train rig used in laboratory experiment 1.

In each scenario, the participants entered the train through the entrances at the short ends and exited it through the exit into the tunnel. This procedure was repeated for five minutes, and consequently each participant evacuated the train more than once during each scenario. Data were collected by observation, and in total, seven video cameras, located both in the train and in the tunnel, were used to record all evacuations. These recordings were then used to estimate quantitative parameters such as flow rates of people and population densities, as well as qualitative aspects, such as interactions between people.

The fact that the experiment was well documented, both in terms of set up, method, and procedure, suggests that it would be possible to repeat it and end up with similar results. Consequently, the reliability of the experiment is deemed high. However, the adopted research strategy implies some validity problems. The fact that only students took part in the experiment is certainly one aspect which suggests that the generalizability of the results is low. In addition, each student evacuated the train a number of times in each scenario, and furthermore, took part in nine scenarios in total. This means that each student evacuated the train many times, and there may have been learning effects which inarguably reduced the external validity of the results even more. It may also have had an effect on the internal validity of the results, in particular, when identified interactions are interpreted. Is, for example, an identified interaction between the participants a result of them having got to know each other during the experiment, or is it an interaction caused by the process studied?

Pattern matching and explanation building was difficult as only one data collection technique was used in the experiment. This implies low construct validity. It was, for example, difficult to interpret certain interactions between people as only observation was used. This is because the interpretation may not necessarily be shared by the participants in the experiment. However, as the primary purpose was to explore and describe, and not explain, it is argued that a sufficiently operational set of measures was adopted to collect the data.

The above discussion suggests that a number of aspects may have affected the quality of the study negatively. The conclusion is that the main benefit of the results generated in the study is the internal comparison between scenarios, i.e., the relative comparison between different train exit configurations in terms of the flow rate of people. In this perspective, it may be considered as beneficial to have included the same participants in many scenarios as the group can be considered as a variable that was held constant during the experiment.

Based on the experiment, it is possible to describe the relationship between a train exit configuration and the flow rate of people. This should, however, be done with the sample of participants in mind, i.e., relatively young, fit and healthy people. Consequently, verification of the results in, for example, a field experiment with non-trained and mixed participants, is necessary to provide additional descriptive knowledge that is generalizable to real settings. Such knowledge would, furthermore, add a dimension to the discussion on the extent to which the findings of the laboratory experiment can be generalized.

Experiment 2: Evacuation of a smoke filled rail tunnel

The objectives of the second evacuation experiment were to study the effectiveness of different way-findings systems in a smoke-filled rail tunnel during an evacuation, and at the same time collect data on human performance and walking speeds. The experiment is presented in Paper III, and a more detailed description of the experiment is provided by Fridolf (2013). Furthermore, the data set related to walking speeds have also been used to provide recommendations on application and design (Fridolf, Andrée, Nilsson, & Frantzich, 2014).

The experiment was carried out in a single bore tunnel which prior to the experiment had been used during the construction of the Southern Link road tunnel in Stockholm. It was supplied with technical installations typical for rail tunnels, such as emergency signs on both sides of the tunnel, which provided light and information on distances to the nearest exits. Furthermore, an emergency exit equipped with a number of technical installations was installed in the end of the tunnel. During the experiment, these installations were combined in order to generate a total of five different experiment scenarios.

In comparison to the first laboratory experiment, the second experiment was larger in size. As it was carried out in an existing tunnel, it can to some extent be considered to be a field experiment. However, as the tunnel was not open to the general public, and, furthermore, to a large extent had to be modified prior to the experiment in order to resemble a rail tunnel, it is characterised, within this thesis, as a laboratory experiment.

In total, approximately 200 m of the 8 m wide tunnel was used during the experiment. An overview of the tunnel is shown in Figure 5. In summary, the tunnel can be divided into two parts:

1. 122 m with a downhill gradient of 10%.
2. 76 m with no inclination.

Furthermore, the second part of the tunnel included a section measuring 32 m in length and 1.5 m in width, which was covered with macadam of size 32-64 mm. It should be noted that the downhill gradient of the first part of the tunnel exceeds typically allowed and practically possible maximum railway ruling gradients. The reason is that the tunnel previously had not been used for railway traffic, but road traffic.

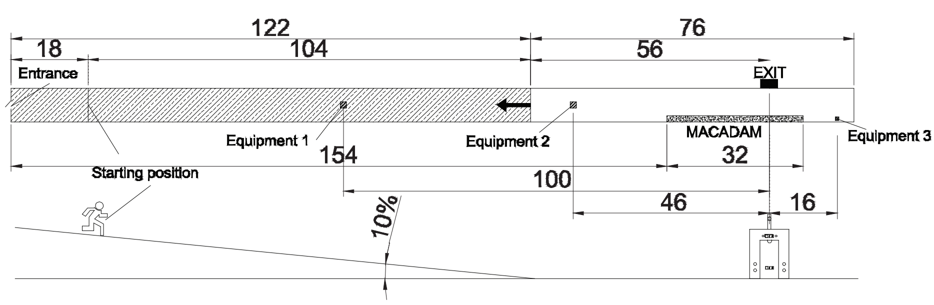

Figure 5. An overview of the tunnel used in laboratory experiment 2. The perspective is from above in the upper part of the figure, and from the side in the lower part.

During the entire experiment, the tunnel was filled with artificial, cold smoke. Acetic acid was introduced as an irritant into the smoke in concentration levels which could cause temporary effects related to a burning sensation in the nose and throat, eye-irritation, and/or coughing. The irritant effects achieved by the acetic acid was, however, very mild.

In total, 100 participants of ages 18-66 years took part in the experiment. The participants were mainly recruited from the general public in Stockholm, but some were also recruited among employees at the Traffic Administration Office in Stockholm. Only a few of them had been walking longer distances in rail tunnels prior to the experiment. The participants took part in the experiment individually, and consequently, no group interactions were studied. Prior to the actual evacuation, they received general information about the experiment. They were told that they would be exposed to an environment similar to a smoke filled rail tunnel, and that their movement and exit choice would be studied.

Before each participant entered the tunnel, he/she was shown a video sequence shot in first person perspective, which illustrated a person travelling in a train that eventually came to a stop inside a tunnel. The participant was told to imagine that it was he/she in the film, and then assisted into the smoke filled tunnel where he/she was told to find a way to safety. The participant did so while followed by a fire fighter who kept a distance of 8-10 m to the participant, at the same time filming him/her with a thermal imaging camera.

In order to enable a reliable and valid analysis of the participants' walking speeds, walking strategies, exit choice and other human behavior activities, a number of data collection techniques were combined. Firstly, observation was done by use of the thermal imaging camera, which recorded each evacuation. As a complement to the video recordings, each participant also filled out an extensive questionnaire after the evacuation. This questionnaire included questions on demographics, the experiment and the participants' behaviors, technical installations and the perceived benefit of these, and the participants' feelings during the experiment. Finally, 65 of the 100 participants took part in an interview after they had filled out the questionnaire. In this interview, which was semi-structured, the participants were shown the video recording of their evacuation and asked to explain their behavior and thoughts during the different sequences of the evacuation. Steps were taken to make sure that both questionnaire and interview questions had been clearly defined, that they were relevant for the purpose of the study, that they were not biased, and that the risk of misinterpretation would be minimal. Among other things, a framework suggested by Foddy (1993) was used in the development of the questionnaire and the interview protocol.

Due to a number of reasons, the quality of the findings generated in the second experiment is deemed to be higher than the first experiment. A number of measures were introduced in order to increase the validity of the study. In addition, rigorous experimental plans were developed before and used during the evacuation experiment in order to guarantee identical treatment of the participants. Similarly, well-defined protocols were laid out prior to the data analysis of the material. This is likely to have increased reliability, i.e., that the study would be able to be repeated by other researchers and that they would generate similar results.

In the experiment, multiple data collection techniques were combined in a triangulating fashion. This strategy likely had a positive effect on the construct validity, as behaviors observed in the video recordings could be confirmed by answers provided by the participants, both in the questionnaire and during the interview. The tactic of using multiple data collection techniques allowed for pattern matching and explanation building during the analysis of the material. For example, the video recordings allowed an analysis of whether or not a participant found and used the emergency exit that had been installed in the tunnel. In other words, the video recordings allowed the question "how effective was a certain exit design in terms of attracting people to it?". However, the video recordings provided little support for explanations of the behavior. This was instead provided by the questionnaire and interview answers, which also allowed the question "why was a certain exit design effective?" to be answered.

Another example relates to the analysis of walking speeds. As in the previous example, the video recordings provided descriptive information on how fast the participants walked in the smoke-filled tunnel, and with what posture. However, only the questionnaire and interview answers could provide possible explanations of their behavior, which could then be linked to the walking speeds. This involved explanations as to why a typical action or behavior was performed. Together, the two examples illustrate aspects that likely increased the internal validity of the findings.

There are a number of factors that possibly also increased the external validity of the experiment. The fact that the participants were recruited from the general public, and that they represented a rather heterogeneous group of people, suggests that the results would be generalizable to a real underground rail transportation system. Furthermore, a majority of the participants rated the degree of realism of the experiment as high, which suggests that the setting was perceived as similar to a real setting. Another factor also suggesting that the external validity of the experiment is high is the fact that the participants took part in the experiment for a relatively long time, and walked almost 200 m before the experiment ended.

Still, the participants had received some information prior to the experiment, and they knew that they were taking part in a scientific study. As an example, stress levels were reported to be rather low in the experiment, and this is possibly due to the fact that the participants felt rather safe and that they were not afraid of getting hurt. It is likely to be the opposite in a real fire in underground rail transportation systems. In addition, all evacuations were done individually. Consequently, the data cannot directly be generalized to a setting in which group interactions may have an effect.

Step 3: Data collection in the field

In the third step of the research strategy, data were collected in a field evacuation experiment executed in the Stockholm Metro. The experiment, which is presented in Paper IV, covered all of the previously studied areas. In other words, it included evacuation of a train in a tunnel, as well as the subsequent evacuation of the tunnel. The objectives of the experiment were to:

1. Collect data on the flow rate of people through train exits during an evacuation of a train in a tunnel, i.e., from the train to the tunnel floor.
2. Collect data on the walking speed of people when moving long distances over an uneven surface in a tunnel.
3. Study exit choice and behavior during evacuation in a tunnel.

The experiment aimed to verify some of the results generated in the previous experiments. To what extent would, for example, the flow rate measurements captured in the first laboratory experiment agree with the same type of measurements in a natural setting with a mixed population? Another aim of the experiment was to generate new data, in particular on walking speeds over uneven surfaces in smoke-free conditions in a rail tunnel.

The experiment was carried out during nighttime and included a total of 135 participants who had been recruited from the general public in Stockholm. The participants represented a broad population of both men and women, with ages varying from 19-76 years. Prior to the experiment, the participants had received some information about the experiment. In part, this involved practical information, but it also included some misleading details. The participants were, for example, informed that the purpose of the experiment was to study what type of information, and which technical aids, that passengers would be helped by during an accident. Thus, explicit information about the true objectives of the experiment was not provided, and the participants were unaware of the fact that they would have to evacuate a train in a tunnel setting. They had been informed, however, that transportation by foot in parts of the metro system could occur at some point during the study.

In summary, the experiment began with all the participants entering a typical metro train (model C20) with an open plan, i.e., an open architecture, which meant that all participants could see each other. The train travelled inside the metro system for approximately 20 minutes, during which it stopped at four different underground stations, although without letting the passengers off the train, before arriving at the test location between the Rinkeby and Tensta underground stations; see Figure 6.

When the train had come to a stop, artificial smoke was produced to resemble a fire in the middle of the train. At this point, the participants were instructed by the train driver through the public address system to leave the train and to move away from the smoke to a safe location. The participants evacuated the train by three available exits, and thereafter moved away from the smoke toward the closest station, i.e., the Rinkeby station. The station was located approximately 400 m away from the train. However, an emergency exit was available already after 200 m, and the participants could choose to evacuate through this if they wanted. No instructions about this had been given, and they were unaware of the exit until they reached it.

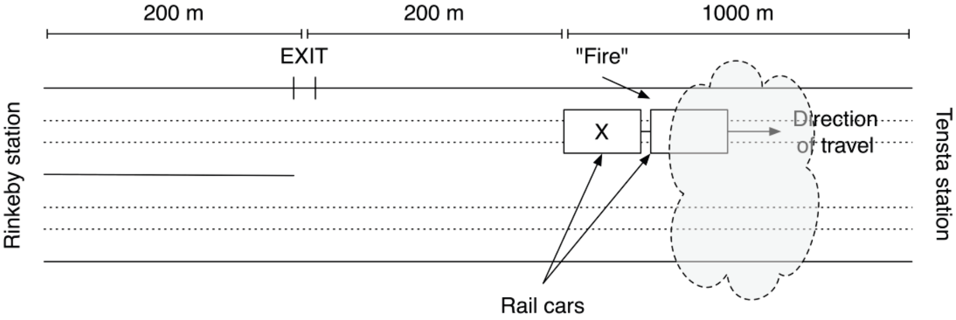

Figure 6. An overview of the tunnel used in the field evacuation experiment. The participants evacuated toward the Rinkeby station, i.e., to the left in the figure. Cold, artificial smoke blocked the passage in the other direction.

As in the second laboratory experiment, multiple data collection techniques were used to collect both quantitative and qualitative information. More specifically, recording by video cameras installed both in the train and inside the tunnel was carried out, and was complemented with a questionnaire study in which all participants took part. Unfortunately, no interviews could be carried out, but the combination of observation and a questionnaire study is still likely to have increased the construct validity of the study, and the internal validity of the findings. This is based on the same arguments as presented in relation to laboratory experiment 2.

A number of factors are also likely to have increased the external validity, i.e., the generalizability of the results. Firstly, the evacuation experiment was performed in a natural setting with representative participants. Furthermore, the participants were partly uninformed about the true purpose of the experiment, and their behavior may therefore be close to what it had been in a real fire in an underground rail transportation system. In contrast to the second laboratory experiment, it also allowed for group interactions to have an effect on the result.

One drawback of the experiment is that it could not be repeated. One run took nearly four hours, and it was not practical to do a second run as this would have affected the everyday traffic in the Stockholm Metro. This means that only one emergency exit design was possible to test in the experiment, and conclusions on whether this design is more appropriate than any other are difficult to draw. However, the performance of the design can be studied in the light of the second laboratory experiment, in which it also was included. This is also true for the other aspects of the study. In this perspective, the laboratory experiments can be seen to have provided valuable data in more or less artificial settings similar to a rail tunnel, and the generalizability of their results can, to some degree, be expressed in the light of the field experiment.

Ethical considerations

Including human participants in research studies on evacuation and human behavior in fire is a necessary step in advancing the science within the field. It would, for example, be practically impossible to examine and to predict the behaviors, responses, and interactions of people without including them in different research activities, such as evacuation experiments. Thus, data from research studies involving human participants are essential. However, when including human participants in different research activities, it is necessary to consider a number of ethical aspects related to the research. Examples, particularly relevant for the evacuation experiments described above, relate to the potential harm, stress, and anxiety of the participants during their participation.

The need to consider different ethical aspects when performing research with human participants has been illustrated by numerous more or less unethical medical research studies in the past (Gunther, 2015; Robson, 2011, p. 195). Typically, the abuse by German doctors during World War II, involving several unethical medical experiments, is one example (Nuernberg Military Tribunals, 1949a, 1949b). Other examples often mentioned are the American Tuskegee Syphilis study (Jones, 1993), Milgram's study of obedience (Milgram, 1963), and the Vipeholm experiments about dental cavities and caries (Bommenel, 2006). These and many other experiments have led to a development of international codes of ethics aimed at protecting the human participants in different research studies. This is true, in particular, for medical research, but such codes have also been developed to cover social sciences.

An extensive summary of previously conducted unethical research studies, as well as the development of ethical codes and legislations is presented by Nilsson (2009, pp. 37-62), who provides this presentation in the light of research on evacuation and human behavior in fire. Based on, in particular, the Nuremberg Code and the Declaration of Helsinki, Nilsson (2009, p. 40) identifies five basic principles that he deems are particularly relevant to be addressed in the field of human behavior in fire:

1. Restriction of harm and suffering
2. Outweighing of risks by benefits
3. Informed consent
4. Right to terminate the experiment

5. Protection of integrity

These five principles are also, to a varying degree, covered by the Swedish Act (2003:460) concerning the Ethical Review of Research Involving Humans, which was introduced in Sweden in 2004.

The main purpose of the Act (2003:460) concerning the Ethical Review of Research Involving Humans is to protect individuals and human dignity when research is conducted (1 §). When it was introduced in 2004, it led to the establishment of a central ethical review board in Sweden. This central ethical review board is responsible for supervision of the law, and is, in addition, supported by six separate regional ethical review boards. According to the Act, research that is performed according to a method with the purpose of affecting a research subject physically or mentally, and which includes an apparent risk of injuring the research subject either physically or mentally, may only be conducted if it has been approved subsequent to an ethical vetting by one of the six regional ethical review boards (4, 6 and 23-24 §).

For this reason, the evacuation experiment in a smoke filled rail tunnel and the evacuation experiment in the Stockholm Metro was reviewed and subsequently approved by the regional ethical review board in Lund, Sweden. Only the first laboratory experiment, in which students evacuated a train in a rail tunnel, was not submitted to the regional ethical review board. This was because the experiment was deemed relatively uncontroversial from an ethics point of view. Still, a number of measures were undertaken to address the five ethical basic principles presented above. As an example, the participants were informed that they at any time could terminate their participation in the experiment. Furthermore, a number of modifications were made to minimize the risks, and to include the benefits, for participation. This involved the execution of a risk analysis prior to the experiment, and the arrangement of a fire safety education to the participants after the experiment had ended.

For the evacuation experiment in a smoke-filled rail tunnel, and the evacuation experiment in the Stockholm Metro, similar strategies were adopted in order to address the five basic ethical principles. Prior to the experiment, the risk of harm and suffering was minimized by preventing individuals showing signs of anxiety and/or depression from taking part in the studies. This was done by administrating a HAD questionnaire (Zigmond & Snaith, 1983) to all participants who had registered their interest in participating in the experiment. In addition, preparations were in place during the experiments to take care of any participant who might display signs of acute anxiety during the experiment, among other things by the presence of a trained fire fighter observing the experiments.

For the most part, the risk of participating in any of the two experiments was related to physical injury. In the smoke-filled rail tunnel, the tunnel walls and any other obstacles were deemed to represent the largest risk to the participants. Therefore, a number of precautions were taken to minimize the probability of physical injury, as well as the consequences of these injuries. This included removing any spikes and other obstacles in the tunnels, and also providing the participants with protective clothes, such as overall, boots, gloves and helmets. In addition, a trained fire fighter with access to basic medical equipment was present at all times, and could intervene if any of the participants were hurt during the execution of the experiments.

In the evacuation experiment in the Stockholm Metro, one of the main risks identified prior to the experiment was that participants might decide to spontaneously evacuate the train before the electric rail in the tunnel had been turned off and grounded. Therefore, in order to avoid electrocution of any of the participants, several observers were present on board the train and located beside the train doors, with the task to stop any spontaneous evacuation. Some of these persons wore yellow vests, others were concealed in the crowd, i.e., played the role of participants.

In order to outweigh the risks by benefits, the participants in both experiments were provided with a short fire education after their participation. The education focused on fire and evacuation safety in metro systems, and the participants were given instructions of how to behave in case of a fire in the metro. After the experiment in the smoke filled rail tunnel, the participants were also offered the opportunity to try using a portable fire extinguisher. The aim of the education was to guarantee that the participants on an individual level would benefit from having taken part in the experiments by making them better prepared for potential future incidents. In addition, the risks were outweighed by benefits on a societal level as the data generated in the experiment could be used to increase the safety of rail tunnels in the future.

In both experiments, the participants were informed about the risks and benefits, as well as several other aspects related to the studies, prior to the experiment. In general, the information included:

1. the overall plan of the research,
2. the purpose of the research,
3. the research method and data collection techniques that would be used,
4. the risks and benefits that the research could and/or would entail,
5. the identity of the responsible research body,
6. the fact that participation was voluntary, and
7. the right of the participant to end their participation at any time.

The information was distributed to the selected participants in written form approximately two weeks before the experiment, and the information was also orally repeated before the experiment. In particular, it was made clear that the participants could terminate their participation at any time, and still receive their compensation for participating. All participants were allowed to ask questions related to the content of the information before they gave their informed consent to participate in the research study.

It should be noted that limited details about the purposes of the experiments were given to the participants in both experiments. Although the participants in the second laboratory experiment were told that documentation of movement in smoke and exit choice was the purpose of the experiment, they were not informed about tunnel layout, visibility conditions, or how eventual emergency exits would be located and designed. In the field experiment, the participants even received misleading information about the true purpose of the experiment. Common in both experiments however, was the fact that the participants were informed that the overall goal of the experiments was to generate findings that could lead to safer rail tunnels in the future.

Both reviewed experiments were documented using multiple data collection techniques, as described above. Therefore, a number of precautions were taken in order to protect the participants' integrity. Firstly, all video recordings, questionnaires, and interviews are stored at a safe location when they are not being used according to current routines at the Division of Fire Safety Engineering, Lund University. This material is only available to a limited number of researchers who were involved in the research studies. Secondly, all information about the participants was erased, and the documented material was decoded. This means that sensitive personal information, such as name and identity, is not connected to the collected data, and that it is not possible to link sensitive information about the participants to the collected data.

A theoretical framework

In Paper I of this thesis, a theoretical framework to describe human behavior in case of fire in underground transportation systems was identified. The framework includes four generally accepted theories and models of human behavior in fire, namely the behavior sequence model, the role-rule model, the affiliative model, and the theory of social influence. These theories and models are not to be employed in isolation from each other, but rather in an overlapping manner, when describing or analyzing human behavior in fire. This is, for example, illustrated by the close relationship between the role-rule model and the behavior sequence model. More specifically, an individual's response to a fire is typically dependent on the contextual role of that person, and this is reflected in the sequences of his/her behaviors.

In order to demonstrate the applicability of the theoretical framework to tunnel fires, a review of past fire accidents in tunnels was carried out based on the suggested framework. The review included fire accidents in both underground rail and road transportation systems. Naturally, the characteristics of these two types of underground transportation systems can vary significantly. As an example, initial conditions can be very different for users of road tunnels compared to rail tunnels. In a road tunnel, the user is typically located inside a car, which he or she is also responsible for. In contrast, a user of a rail tunnel is likely to travel in a train with many other passengers. This will have an effect on the users' overview and control of the situation, crowd density, and so on. In addition, two different systems of the same transportation mode can also be very different. This is, for example, demonstrated when a comparison is made between an entire metro system, which may include numerous underground stations and a network of tunnels, and a simple, single-bore rail tunnel.

The differences between, as well as within, different transportation modes are likely to affect the specific behavior of people in case of a fire. However, as the review in Paper I illustrated, the underlying mechanism can still be described by the same theoretical framework. The review also demonstrates that is not unreasonable to believe that the already existing theories and models introduced in Paper I can be applied also in the context of underground transportation systems and tunnels. In this chapter, the four theories and models of the suggested theoretical framework are presented.

Behavior sequences

It has been known for relatively long that people in a fire do not necessarily evacuate a building at the first sign of an emergency. In contrast, time may be spent interpreting the first cues of the emergency, which forms the basis for a decision on how to act in the given context and situation. According to Canter et al. (1980), this process can be described by a so-called behavior sequence model.

Canter et al. (1980) developed the behavior sequence model by carrying out multiple case studies of fires that had occurred in domestic, multiple occupancy and hospital fires. In total, 198 fire victims from 28 fires were interviewed about what had happened from the time they were aware that something was out of the ordinary. This allowed Canter et al. (1980) to break the individual behaviors down into single acts, while at the same time, documenting the position in the sequence of events, as well as the individual's physical location in the building.

Based on the a statistical analysis of the acts that the fire victims had undertaken during the fires, so-called decomposition diagrams were created for each of the occupancy types. These diagrams described the association between two or more acts, and furthermore, the strength of the association. Based on the decomposition diagrams, Canter et al. (1980) could conclude that although there were notable variations between the occupancy types, characteristic patterns of behavior occurred in all occupancies.

With this in mind, a general behavior sequence model was proposed; see Figure 7. The general model summarizes a number of recurrent acts from the domestic, multiple occupancy, and hospital fires that were studied. Consequently, it facilitates generalization of human behavior in fire, independent of setting. As can be seen in Figure 7, the behavior sequence model can be described by three sequence categories, or so-called nodal points:

1. Interpret
2. Prepare
3. Act

Each of these nodal points constitutes a behavior sequence, i.e., a sequence of consecutive actions that people may perform in a fire. Figure 7 also illustrates that as the sequence of behavior unfolds, the potential acts increase. This means that statements about initial acts and behaviors are likely to be made with a higher degree of confidence than about acts later in the sequence. Furthermore, Canter et al. (1980) concluded that acts in the lower part of Figure 7 are more likely to be dependent on the occupancy context.

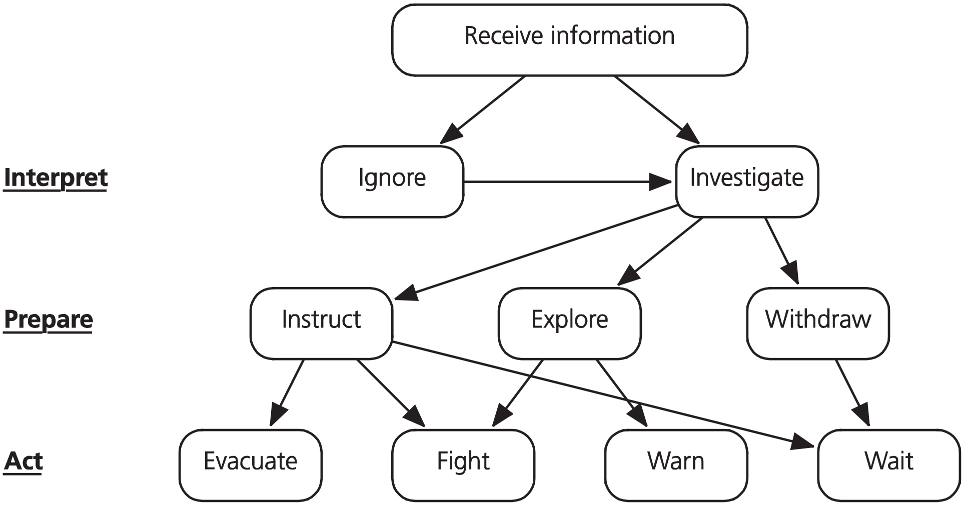

Figure 7. The behavior sequence model is a general model that can be used to describe the sequence of consecutive actions that people perform in a fire.

It is emphasized that the behavior sequence model is a general model which summarizes the most recurrent behaviors identified by Canter et al. (1980). Hence, it does not explain the specific behavior of each individual in a fire, and behavior sequences do not necessarily follow the arrows in Figure 7. An individual may, for example, act by evacuating after having explored a fire situation, or simply ignore the findings of such an exploration. Still, Figure 7 presents a valuable summary of the sequence categories that an individual may typically experience in a fire.

The behavior sequence model can be used to describe why people in a rail tunnel fire do not necessarily start to evacuate at the first sign of danger. Typically, information and fire cues are scarce and ambiguous in the initial stages of a fire. The cue could, for example, be the smell of smoke. Such a vague signal is not likely to initiate spontaneous evacuation. Instead it can be expected to be ignored, or at best to initiate an investigating behavior that can reduce the uncertainties about the situation. This type of behavior was, for example, identified in the fire at Kings Cross Station, which also demonstrated that the response to ambiguous cues and the decisions taken in uncertain situations may differ greatly between different people (Canter et al., 1992; Donald & Canter, 1990; Fennell, 1988; Wildt-Persson, 1989). Another example of when the behavior sequence model can be used to facilitate understanding of human behavior in rail tunnel fires is the fire in the Kitzsteinhorn funicular tunnel, mentioned in the introduction to this thesis (Bergqvist, 2001; Carvel & Marlair, 2011, p. 12; Fraser-Mitchell & Charters, 2005, pp. 545, 547-548, 551; Larsson, 2004; Martens & Jenssen, 2012, p. 81; Schupfer, 2001). Prior to the train coming to a stop in the tunnel, people on the train had seen both smoke and flames. However, these cues were not interpreted as an immediate risk.

In conclusion, the initial decisions that a person makes in the early stages of a rail tunnel fire can be expected to be associated with great uncertainties. However, as the person receives more information about the fire, the uncertainty associated with the decision-making is reduced. It is, thus, more likely that a person will be able to correctly interpret, prepare, and act accordingly, as more fire cues are provided. This is particularly true if the cues are coherent.

The role-rule model

By developing the general behavior sequence model, Canter et al. (1980) demonstrated that uncertainty reduction is an important aspect when human behavior in fire is described. In addition, they illustrated that behavior sequences, i.e., how a specific person responds to a fire, are highly dependent on the role of the person. Sometimes this so-called role-rule model is described implicitly within the behavior sequence model. However, in this thesis, it is separated and discussed as a specific model to facilitate the understanding of human behavior in fire.

When reviewing their general behavior sequence model, Canter et al. (1980) could find consistencies among the behavior of people from similar groups. During fires in hotels, staff, for example, did behave differently from the guests. In hospital fires, staff continued with their duties to patients, and in dwellings, parents secured their children's safety. In other words, the behavior of people seemed to be highly dependent on the contextual role in which they saw themselves (Canter, 1990b; Pigott, 1989).

Eventually, a role-rule model was formulated, suggesting that a person's behavior in a fire is guided by a set of expectations about his/her purpose in a particular context (Canter, 1990b; Canter et al., 1980; Tong & Canter, 1985). These general expectations form a framework, which builds a person's role. Each role is associated with a set of behavior rules, which can be seen as guiding principles associated with the role that a person has adopted. Evidently, these guiding principles will influence the actions taken in a fire situation, i.e., the behavior sequence. Another important conclusion is that the relative roles of people in non-fire situations affect their behavior in a fire. More specifically, it was shown that people maintain their contextual roles in non-fire situations also during fires.

In rail tunnel fires, contextual roles and associated rules can be expected to affect the sequence of consecutive actions that people perform. Consequently, members of the general public, such as passengers, can be expected to interpret, prepare and act differently on fire cues compared to authoritative personnel, such as staff or police officers. This has, for example, been identified in the fire at Kings Cross Station (Canter et al., 1992, p. 147), in which it was also concluded that people will try to carry out their intended objectives also in fires, unless there is strong incentive not to do so. Another example of where members of the public behaved differently from staff is provided by a fire that occurred on a train in the Zürich Metro in 1991 (Fermaud, Jenne, & Müller, 1995; Frantzich, 2000, p. 13; Fraser-Mitchell & Charters, 2005, pp. 545-552; Martens & Jenssen, 2012, pp. 78, 80-81). The fire in the Zürich Metro also illustrates that people tend to keep their everyday role also in an extreme situation such as a fire.

The affiliative model

A third model that greatly aids the understanding of human behavior in fire is the affiliative model developed by Sime (1983, 1984, 1985). It was developed as a response to the so-called physical science model, which assumes that people in an emergency always choose to evacuate via the shortest evacuation route. In contrast to the physical science model, the affiliative model assumes that people are more likely to move to familiar places and people in a threatening situation.

In a fire situation, this means that people are likely to evacuate the same way they entered a building, simply because it is familiar. Consequently, the model may also be used to explain why people avoid escape routes, e.g., emergency exits, which traditionally are not used during normal operations. In addition, the affiliative model also suggests that evacuation is likely to take place within groups to which a person has previous ties, such as family members.

The fact that people faced with a fire tend to move to familiar people have also been shown to have an effect on the interpretation of ambiguous cues, and consequently, the time to evacuate. People who are separated from their family, for example, have been shown to respond very quickly to initial cues in a fire (Sime, 1983, p. 38). In contrast, people who are attached to their group when receiving an initial cue have delayed their decision to evacuate until there have been clear signs of a fire threat. One possible explanation for this could be that initial cues about a fire prompt individuals who are separated from their group to go looking for them, even if the cues are ambiguous. On the other hand, individuals of complete groups may gain a feeling of security for being part of their group.

As rail tunnels are unfamiliar to the majority of the people using them for transportation, the affiliative model can be used to explain peoples' reluctance to evacuate a train in a tunnel. Naturally, unfamiliarity is not the sole reason, and the behavior sequence model may provide additional reasons to this reluctance. The affiliative model can also be used to explain why people in rail tunnel fires may be more inclined to evacuate toward any of the tunnel portals rather than the available emergency exits, and furthermore, why groups may form during a rail tunnel evacuation. This was the case during the fires in the Zürich Metro and the Baku Metro, where groups of people evacuated to underground stations while holding on to one another (Carvel & Marlair, 2011, p. 14; Fermaud et al., 1995; Frantzich, 2000, p. 13; Fraser-Mitchell & Charters, 2005, pp. 545-552; Martens & Jenssen, 2012, pp. 78, 80-81; Rohlén & Wahlström, 1996; Shields & Boyce, 2004).

Social influence

As was discussed in the previous section, the presence of others has been shown to affect a person's decision to evacuate. In this thesis, this is considered as a separate part of the theoretical framework presented in Paper I, and is termed social influence. According to the concept, the presence of others is likely to affect a person's sequence of behaviors during a fire. Latane and Darley (1968), for example, demonstrated that single individuals are more prone to react to fire cues compared to individuals who are part of a group. Furthermore, Latane and Darley (1968) also illustrated that single individuals respond more quickly to these cues.

Social influence can be divided into two categories, namely normative social influence and informational social influence (Deutsch & Gerard, 1955). In this categorization, normative social influence is defined as an influence to conform to the positive expectations of another. Positive expectations here refer to expectations that lead to a positive feeling when fulfilled by another, i.e., the prevalent norms. In other words, people in general are afraid of standing out or making fools of themselves, and their individual judgments therefore often conform to the believed expectations of others.

Informational social influence is instead defined as an influence to accept information obtained from another as evidence about reality. This suggests that people will look to other people for information in ambiguous situations, and when uncertain about how to behave. As this generally is the case in fires, in particular in the early stages, social influence is likely to affect the sequence of individual behaviors that unfolds during a fire.

In rail tunnel fires, the effect of social influence can be both positive and negative. The normative part can inhibit peoples' response, thereby prolonging the total evacuation time. It was suggested earlier, for example, that the affiliative model might explain peoples' reluctance to evacuate a train in a tunnel. This reluctance is most likely amplified by the fact that using emergency door openers and jumping out of a still-standing train is not considered as the norm. On the other hand, informational social influence can have a positive effect if people see others evacuate. This is a clear cue that they themselves should respond, and can evidently reduce the initial uncertainties related to the decision making as illustrated in the behavior sequence model. Examples of when social influence has affected behavior in the setting of road tunnels are many. More specifically, it has been observed that people are more inclined to leave their vehicle when other people do so as well. Examples in past rail tunnel fires also exist, such as in the case of the fire in the Zürich Metro, where people looked at each other for information on what to do in the ambiguous and uncertain situation that existed (Fermaud et al., 1995; Frantzich, 2000, p. 13; Fraser-Mitchell & Charters, 2005, pp. 545-552; Martens & Jenssen, 2012, pp. 78, 80-81).

Applicability

In Paper I of this thesis, the applicability of the four generally accepted theories and models on human behavior in building fires that form the basis for the theoretical framework was demonstrated, as well as its applicability for fires in underground transportation systems. It is clear from the review that a discussion of human behavior in tunnel fires can benefit from the use of a theoretical framework. In this perspective, it may be argued that the theoretical framework can facilitate the understanding of human behavior in the event of fires in rail tunnels.

A number of similar studies to support this argument were carried out in the past (Beale, 2002; Bodart, Marlair, & Carvel, 2004; Canter et al., 1992; Frantzich, 2003; Frantzich & Nilsson, 2006; Fraser-Mitchell & Charters, 2005; Marlair, Lecoze, Woon-Hyung, & Galea, 2004; Martens & Jenssen, 2012; Shields & Boyce, 2004). Fraser-Mitchell and Charters (2005, p. 543), for example, concluded that the behavior of people in tunnel fires is similar to that in building fires. In a review of past tunnel fire accidents, they illustrate, furthermore, the applicability of both the behavior sequence model and the role-rule model. In addition, they were able to identify behaviors that typically could have been explained by the affiliative model.

The consistency in people's behavior during emergencies, independent of setting, was also demonstrated by Canter et al. (1992, pp. 135-136). In relation to an analysis of the fire at Kings Cross Station in 1987, they discussed the significance of the location of the station. Canter et al. (1992, pp. 135-136) concluded that underground facilities, such as an underground station, pose a unique environment to people. However, they were not able to identify any specific types of behavior due to this. In contrast, they illustrated the applicability of more or less all of the models included in the theoretical framework presented in this chapter.

Also Shields and Boyce (2004) demonstrated the applicability of a number of the theories and models of the theoretical framework suggested in this chapter. In 2004, they presented an extensive review of the behavior of people in past fire accidents in tunnels. In the study, numerous observations were identified, some of which can be related to the theories and models developed for buildings. Among other things, Shields and Boyce (2004) concluded that a basic behavioral fire response model, similar to the behavior sequence model, as well as the affiliative model, were likely to be applicable for evaluation of human behavior in tunnel fires.

Additional support for the applicability of the theoretical framework is provided by a number of previously conducted empirical studies. For example, the benefit of utilizing the behavior sequence model and the affiliative model was illustrated during an evacuation experiment in an underground metro station (Proulx, 1991; Proulx & Sime, 1991). With the models, it was demonstrated that precise information about a fire is necessary for a rapid and successful evacuation.

In other studies, social influence was identified as having a significant effect on the results of evacuation experiments, both in terms of response time and exit choice (Boer & Veldhuijzen van Zanten, 2005; Frantzich, Nilsson, Kecklund, Anderzén, & Petterson, 2007; Nilsson & Johansson, 2009; Nilsson, Johansson, & Frantzich, 2009). Thus, the applicability of the suggested theoretical framework is not only demonstrated by other previously conducted reviews of past fire accidents in underground transportation systems. It is also illustrated by empirical research in tunnel environments.

Another fact that also supports the use of the theoretical framework for tunnel fires is the particular consistency of people's behavior in fire in different buildings and occupancy types (Canter, 1990a). The behavior sequence model, for example, was derived from observations in multiple occupancy building types and is, by definition, a general model. Altogether, the above discussion suggests that the theoretical framework presented in this chapter is applicable to describe the behavioral activities of people in underground transportation system fires. Consequently, it may be applied in order to facilitate the understanding of human behavior in rail tunnel fires. However, this does not mean that the framework can be used to describe the exact behavior pattern of every individual in a tunnel fire. Instead, as have been pointed out by Frantzich (2003), these theories and models can be used to describe general behavior of an average individual in this setting.

Train evacuation

In Paper II and IV of this thesis, experimental findings of peoples' capability to evacuate a train in a rail tunnel are presented. The findings of both experiments are summarized in this chapter. Prior to that summary, the most important findings of previously conducted empirical studies performed in rail tunnel settings are presented. The presentation is done in order to provide an overview of the current knowledge, and to facilitate a comparison between the contribution by Paper II and IV, and previously conducted studies.

The majority of the previous research have been executed as experimental studies, but it should be noted that qualitative investigations are also available (Kecklund, Arvidsson, & Petterson, 2012; Petterson, 2009; Petterson, Arvidsson, & Kecklund, 2012). These qualitative studies have, among other things, highlighted areas for improvement related to train evacuation from a human-technology-organization perspective. They may, therefore, provide additional valuable information to complement the studies presented below.

Previous studies

Previous rail tunnel evacuation experiments that have been conducted in the field is particular rare. Prior to the work presented in this thesis, one of the few existing field studies was performed by Frantzich (2000) who, among other things, made flow rate measurements of an upright-standing train in the Stockholm Metro. In the experiment, 143 participants had to overcome a vertical distance between the train and tunnel floor corresponding to approximately 1.4 m. The lateral space between the train and the tunnel wall was limited, but was generally never narrower than 1 m. Observed flow rates varied between approximately 0.1-0.2 persons/second (p/s) in a first scenario, and between 0.4-0.6 p/s in a second scenario that included the same participants. Possibly, the higher flow rates in the second scenario were due to the fact that the participants had gone through the same procedure just one hour earlier. The lower flow rates in both scenarios were identified as an effect of the presence of an emergency ladder in the train exit, which indicates that people take longer to evacuate a train in small steps via a ladder compared to jumping or climbing out directly.

During the experiment in Stockholm Metro, Frantzich (2000) observed that some people were reluctant to leave the train due to the height difference between the train and tunnel floor. In addition, he noted that the majority of the participants kept their initial choice of exit. In other words, when queues had dissolved around some of the train exits, people still kept queuing to evacuate the train by the exit they had initially chosen. Another interesting observation made in both scenarios was that queues not only arose inside the train, but also outside in the tunnel parallel to the train. These queues were mainly caused by emergency ladders, which were used in some of the exits to facilitate the evacuation. More specifically, the ladders effectively reduced the already limited width of the lateral space available between the train and the tunnel wall, thus making it even more difficult for people to pass.

The formation of congestions in rail tunnels during train evacuation was also identified in a laboratory evacuation experiment (Oswald, Kirchberger, & Lebeda, 2008; Oswald, Lebeda, Schneider, & Kirchberger, 2005; Oswald, Schjerve, & Lebeda, 2011). In the experiment, 450 fully informed participants evacuated a metro train in an environment similar to a tunnel environment. The experiments were performed outside, but the participants were instructed to evacuate onto a 0.75 m narrow walkway, which was located 1.15 m below the train floor. Average flow rate capacities through the train exits were reported in the order of 0.25 p/s per m of door width, i.e., approximately 0.3 p/s (the door was 1.3 m wide). During the evacuation of the train, the walkway became heavily congested. Therefore, it became very difficult for people inside the train to merge into the flow of people who had already exited the train and were located on the walkway. A particularly interesting observation was that priority seems to have been given to the participants onboard the train. More specifically, the participants on the walkway allowed people, where possible, to evacuate the train. This caused the train to be emptied in a sequence similar to a domino effect, where all participants at the door closest to the front of the train were allowed to disembark first. Thereafter, the second closest door was given priority, and so on. Consequently, this caused the participants in the rear end of the train to stand still in queues for a very long time.

In addition to empirical studies that were conducted in rail tunnels, or similar settings, a number of experiments have also been carried out in environments with unlimited lateral space. In these environments, the lateral space outside the train is less likely to be crowded as people are not forced to stay next to the train when they have exited it, which could lead to higher flow rates. Flow rates were, for example, reported on the order of 0.9 p/s per m door width in evacuation experiments from both commuter and metro trains where participants evacuated the train onto the ground located 0.65-1 m below the train floor (Oswald et al., 2008; Oswald et al., 2005; Oswald et al., 2011). An important conclusion from these experiments is that no significant relationship was identified with the exit height. In other words, the average flow rate capacity did not seem to be affected whether the vertical distance between the train and tunnel floor was 0.65 or 1 m.

In another announced field experiment, comprising 218 fully informed participants, a train was evacuated onto a platform with unlimited lateral space in a rail tunnel, i.e., an underground station (Capote, Alvear, Abreu, & Cuesta, 2012a; Capote, Alvear, Abreu, Cuesta, & Alonso, 2011, 2012b). Flow rate capacity measurements were made at one exit, and averaged 0.57 p/s during the entire evacuation. As the platform offered an unlimited lateral space to evacuate onto, no congestion arose outside the train. However, significant deference behavior was observed inside the train. This was due to two flows of people, coming from opposite directions and meeting at the train exit, and having to share one available single door exit. Initially, men were observed to defer to women. However, as the population density increased around the exit, the participants instead alternated to leave the train through the exit, independent of gender. The outcome of the experiment was used as input data to the STEPS egress model (Capote et al., 2012a), which was used to explore the impact that crew procedures may have on a train evacuation.

There are also other examples of data being collected to verify and validate egress models in order to improve their predictive capabilities. Data sets from different types of announced laboratory evacuation experiments in the US have, for example, been used to validate and verify the railEXODUS egress model (Galea, Blackshields, Finney, & Cooney, 2014; Galea et al., 2013). In one of these studies, 84 people evacuated a train onto a high platform with unlimited lateral space a total of 8 times with varying lighting conditions in the train. On average, the flow rates were observed to be 0.86 p/s under normal lighting conditions, and 0.87 p/s under emergency lighting conditions. Unfortunately, no report of the train door width is given.

In addition to experiments in upright standing trains, Galea and Gwynne (2000) have conducted an evacuation experiment in an overturned rail carriage. During the announced laboratory experiment, the participants evacuated at the end exit of a rail carriage that was resting on its right side. Flow rate capacity measurements were made in two different scenarios: one without smoke and one with non-toxic smoke. The measurements were made at the rail carriage end door, which measured 0.8 by 1.96 m. In the scenario with smoke present, Galea and Gwynne (2000) observed an average flow rate capacity through the door equal to 0.08 p/s. With no smoke present, that number increased to approximately 0.15 p/s.

In all of the above-mentioned studies, data on flow rates were generated in experimental studies. These were performed both in field and laboratory settings. Furthermore, they were conducted in rail tunnel environments with limited lateral space, and in environments with unlimited lateral space. Another source of information, which may provide an increased understanding on pedestrian dynamics, is from studies of passenger flow through train exits during normal conditions. Such a study was done by Norén and Winér (2003) who, by adopting a case study methodology in which they observed passengers entering and exiting trains at different stations, were able to generate large amounts of data related to the flow rate capacity of train exits. These measurements, as well as the observations made in all of the other above-mentioned experiments, are summarized in Table 6. The summary also includes the contribution of Paper II and IV.

Contribution

In terms of train evacuation in rail tunnels, the main contribution of Paper II and IV consists of new descriptive data on flow rate capacities and behaviors in environments with limited lateral space. As few previous studies have examined the potential effect of different train exit configurations, Paper II fills an existing gap by adding new knowledge on this topic. The results presented in Paper II are, however, associated with a number of limitations affecting, for example, the generalizability of the results. To some extent, this is compensated for by the field experiment presented in Paper IV. In addition to quantitative information on flow rates of people, Paper IV also includes information about installations and technical aids that the participants stated would have increased their ability to safely exit the train.

In the laboratory evacuation experiment presented in Paper II, different train exit configurations were used to examine the effects on the flow rate of people through the train exit in a rail tunnel setting. In terms of exit design, five variables were selected and combined to produce a total of 18 different scenarios. The variables are presented in Table 4, and a description of how these variables were combined to produce the different scenarios is available in Paper II.

The average flow rate of people in each scenario was estimated by plotting the cumulative number of evacuated participants against time. Subsequently, a linear regression analysis using the method of least squares was performed. As the regression line fit the data very well in each scenario, the slope of the line was used to describe the flow rate of people. The main benefit of this representation method is that the flow rate of people can be presented in a way that emphasizes the related uncertainties, i.e., the variations of the flow rate of people, in each scenario. This would not have been possible if the flow rate of people had been estimated by simply dividing the total number of participants that had exited the train by the duration of each scenario.

As demonstrated by Table 6 in Paper II, the generated flow rates of people are similar in all 18 scenarios. More specifically, they averaged about 0.5 p/s in almost every scenario. It is only possible to distinguish a deviation in three scenarios (1, 9 and 10). In two of these (1 and 10), an emergency ladder was present in the train exit, which indicates that the flow rate capacity of a train exit is affected negatively by the presence of an emergency ladder. This finding is supported by a previous study in a field settings (Frantzich, 2000), and suggests that although emergency ladders may be beneficial to vulnerable groups, e.g., senior citizens and disabled people, their presence may also reduce the overall flow rate capacity of a train exit.

Table 4. A list of the variables combined in the laboratory evacuation experiment.

Variable	Setting	Description
Tunnel floor material	Concrete	Even tunnel surface with floor material of concrete.
	Macadam	Uneven tunnel surface with floor material of macadam (15-24 mm).
Train exit height	High	Vertical drop from train to tunnel floor of 1.4 m.
	Low	Vertical drop from train to tunnel floor of 0.7 m.
Presence of emergency ladder	Yes	Emergency ladder present in train exit.
	No	No emergency ladder present in train exit.
Lighting conditions	Normal	Lit train and two emergency lights in the tunnel providing 1 lux at floor level.
	Increased	In addition to normal, two halogen spotlights located under the train exit illuminating the tunnel floor.
	Failure	Only two emergency lights lit in the tunnel.
Presence of extra handles	Yes	Three extra vertical handles installed in train lobby. More specifically one in the centre and one on each side of the train exit.
	No	No extra handles installed.

In practical application, the differences in flow rate capacity between most of the scenarios are negligible. It is, however, difficult to determine what the cause of this result is. Should, for example, the absence of differing flow rates between the scenarios be interpreted as an indication of a weak correlation between the train exit configuration and the flow rate of people? Or is the absence related to the fact that a young and relatively healthy sample of participants was used that, in addition, evacuated the train in each scenario multiple times? Or is it due to the fact that the data were generated in a controlled, laboratory setting in combination with other aspects not mentioned here?

Certainly, this is a quality problem of the laboratory evacuation experiment presented in Paper II. However, it should at the same time be noted that the two groups of participants generated nearly identical flow rates with the only differences being the type of floor material in the tunnel. It is, therefore, not unlikely that the majority of the variables included in the study had a very limited effect on the flow rate capacity of the train exit. Exit height, lighting conditions and handles may simply be variables and installations that are of little practical use to young and relatively healthy people.

The observed flow rates presented in Paper II are higher than in most previous evacuation experiments in which the lateral space was limited (Frantzich, 2000; Oswald et al., 2008; Oswald et al., 2005; Oswald et al., 2011). One possible explanation is that the participants represented a relatively young and healthy population, who, furthermore, repeated the experiment many times while wearing no jackets and carrying no luggage. Another possible explanation is that the width of the train exit was relatively great. In fact, the width of 1.7 m allowed two separate queues to form inside the train and for two people to exit the train at the same time. The only requirement for two participants to exit at the same time was that there was enough space for them to do so in the tunnel.

The finding that people in the tunnel to a great extent limited the flow rate capacity of the train exit, independent of configuration, was a very important conclusion of Paper II. The experiment demonstrated that participants in the train were not able to exit it until there was enough space in the tunnel to exit onto. This space was sometimes created by gaps in the flow of people in the tunnel. However, many times people in the tunnel also deferred to allow people to exit the train. This was either done by reducing their walking speed or simply by stopping, and was often complemented with some form of communication, i.e., by a gesture, eye contact, spoken words or a combination of these. Similar conclusions have been drawn from previous studies with limited lateral space (Oswald et al., 2008; Oswald et al., 2005; Oswald et al., 2011).

The field evacuation experiment, presented in Paper IV, overcomes some of the disadvantages of the laboratory experiment presented in Paper II. In particular, this is due to the fact that the experiment was performed in a natural rail tunnel setting. In addition, the 135 participants consisted of non-trained individuals in the ages of 19-69 years who had been recruited from the general public in Stockholm. This also improved the overall quality of the generated data.

In the field evacuation experiment, an unmodified rail car of model C20 was used. Consequently, flow rate capacity measurements were made only for one single train exit configuration. The rail car had been prepared so that only the three exits closest to the rear end of the train were functioning during the evacuation. This allowed the evacuation to proceed for a couple of minutes. In the initial period of the evacuation, queues formed around all three doors as people were exiting through them into the tunnel. The distribution of participants was, however, not optimal. Consequently, the queues dissolved at different times at the different exits. Yet, very few participants reconsidered their initial train exit choice. Thus, they continued to queue in the train although other exits were available. This finding conforms to what was also seen in previous studies (Frantzich, 2000).

In Paper IV, the flow rate of people is not presented as the slope of the line generated in a linear regression analysis, as was done in Paper II. Instead, the presentation is done in time intervals of 30 s, as illustrated in Figure 8. Figure 8 also includes the flow rate of people in the tunnel at the rear end position of the train, more specifically through a cross section between the tunnel wall and the train by the end of the train. In Figure 8, train exit 1 represents the exit located closest to the rear end of the train, train exit 2 the second closest, etc. To facilitate a comparison between Paper II and IV, a presentation of the cumulative number of evacuated participants against time in the field evacuation experiment is presented in Figure 9.

In Figure 8, it seems as if the flow rate of people varied in each exit over the different time intervals. In other words, the flow rate of people both increased and decreased during different time sequences of the evacuation. This is, however, not as apparent when the cumulative number of evacuated participants is presented as a function of time; see Figure 9. On the contrary, the trends in Figure 9 reveal a relatively uniform relationship between the cumulative number of evacuated participants and time, as long as queues existed. Although it is possible to discern a decline, especially in train exit 2 and 3, a linear regression analysis using the method of least squares demonstrated that the slope of the line fit the data well in all exits.

Selected results of the linear regression analysis for each exit and the rear end of the train are presented in Table 5. The presentation is limited to the parameter describing the slope of the line, i.e., the average flow rate of people at each position. As for the laboratory evacuation experiment, the presentation is done with a 95% confidence level to emphasize the variation related to the average flow rate of people. The adjusted R square value (R^2) is included as it illustrates the applicability of the slope of the line as a descriptor of the flow rate of people. It should be noted that the flow rate capacity estimations presented in Table 5 were done only for the time periods when there was still a queue at the respective exit. As an example, the queues resolved at train exit 1 earlier than in the other two exits, which is also discernible in Figure 9. This explains why the flow rate of people is reported as slightly higher in train exit 1 compared to train exit 2, although the data in Figure 9 may give the appearance of the opposite.

In Paper IV, the average flow rates are reported to vary between 0.19-0.22 p/s for the entire evacuation. The information in Table 5 lie in the same range, but the main benefit is that it also transparently expresses the variation in the measurements. Although the reported values are significantly lower than in the laboratory evacuation experiment presented in Paper II, the values conform to previously generated data in with limited lateral space (Frantzich, 2000; Oswald et al., 2008; Oswald et al., 2005; Oswald et al., 2011).

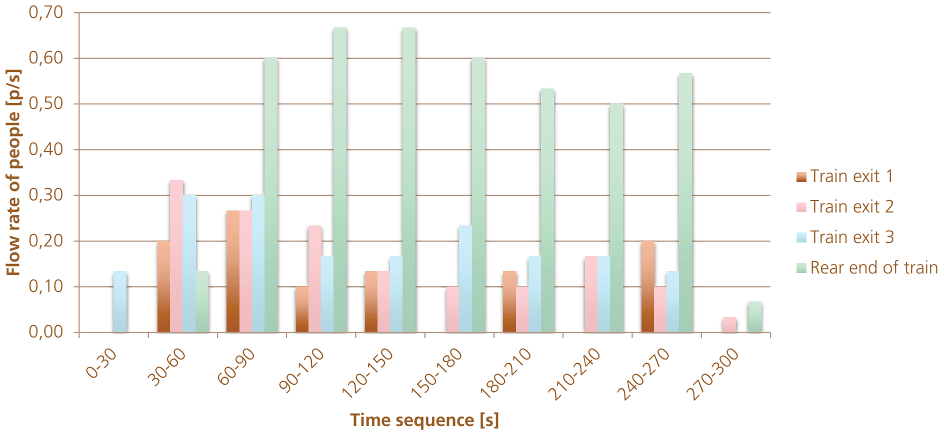

Figure 8. The flow rate of people during the field evacuation experiment. Presentation is done in time intervals of 30 s, where t = 0 s represents the time when the train driver opened the doors.

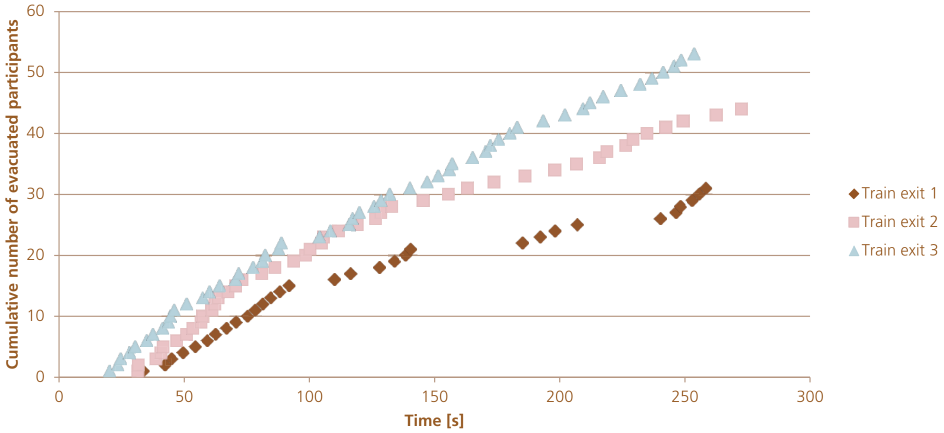

Figure 9. The cumulative number of evacuated participants as a function of time in all three train exits during the field evacuation experiment. The queue at train exit 1 resolved after approximately 140 s, and in train exit 2 and 3 after approximately 270 s.

Table 5. The flow rate of people through each train exit and at the rear end of the train during the field evacuation experiment.

Location	Flow rate of people [p/s]	R^2
Train exit 1	0.18 ± 0.02	0.97
Train exit 2	0.17 ± 0.01	0.95
Train exit 3	0.21 ± 0.01	0.99
Rear end of train	0.59 ± 0.00	0.99

It is concluded in Paper IV that many of the participants in the field evacuation experiment believed that they were able to exit the train safely on their own. More specifically, they rated their ability to do so as high. However, at the same time, 70% of the participants expressed one or more difficulties related to the evacuation of the train. This may seem as contradicting results, or as the result of self-enhancement, but an alternative explanation is provided in Paper IV. A participant may, for example, have felt that he/she was able to evacuate the train safely on his/her own, but at the same time, may have experienced one or more difficulties while doing so.

Perceived difficulties in exiting the train are presented in Paper IV, and were in general associated with the height difference between the train and tunnel floor and with crowding or other people being in the way. The latter supports the conclusion presented in Paper II, i.e., that people in a tunnel likely limit the flow rate capacity of a train exit with limited lateral space. In Paper IV, a number of suggestions on how to increase the ability to evacuate a train in a tunnel are presented as suggested by the participants. Handles, an emergency ladder, and a reduced height difference between the train and tunnel floor, such as with an elevated escape walkway, were typically mentioned.

In addition to the results presented above, Paper IV also discusses a helping behavior identified among the participants. Approximately one quarter seem to have provided assistance to other participants, in particular during the evacuation of the train. Furthermore, as many as one third of the participants stated that they had received assistance. A clear example of this is illustrated in a series of images, provided in Paper IV; see Figure 13-Figure 16. As the participants had no previous known relation to each other, the finding implies that this type of behavior may also occur during a real evacuation.

Summary

Prior to the laboratory and field evacuation experiment presented in Paper II and IV, only a very limited number of research studies had examined train evacuation in rail tunnel settings, particularly with limited lateral space. Consequently, Paper II and IV provide insightful information on train evacuation in rail tunnels in general, and flow rate capacity of train exits in particular. For comparison, the observations made in the laboratory and field evacuation experiments are summarized in Table 6, together with the observations made in all of the above-mentioned previous studies. It provides an overview of the current knowledge on train evacuation in tunnel environments. However, it should be noted that Table 6 presents nothing about the limitations of each study. If the data are to be used for, for example, application and design purposes, this must be considered.

The results presented in Paper II indicate that different train exit configurations may have a very limited effect on the flow rate capacity. More importantly, the experiment confirmed previous observations related to the limiting effects that people in the tunnel may have on the flow rate capacity of a train exit. This finding was also confirmed in the field evacuation experiment.

In general, the laboratory evacuation experiment produced very high flow rates. A number of explanations are possible, and it is not unlikely that the multiple evacuations each participant performed affected their ability to exit the train. Similar observations were, for example, made by Frantzich (2000) who observed 2-4 times higher flow rates when participants evacuated a train in a tunnel a second time. Although the data may be used for internal pairwise comparison between the different scenarios, the measurements made in the field evacuation experiment likely provide a better description of a real rail tunnel evacuation.

Table 6. A summary of conducted research studies related to train evacuation both in and outside rail tunnels. Reproduced values have been rounded off to include no more than two decimals.

Reference	Space	Width [m]	Height [m]	Flow [p/s]	Note
Paper IV	~1 m	1.4	1.4	0.18*	Train exit 1
	~1 m	1.4	1.4	0.17*	Train exit 2
	~1 m	1.4	1.4	0.21*	Train exit 3
Paper II	0.85 m	1.7	1.4	0.33	Concrete, 1.4 m, ladder, normal lighting
	0.85 m	1.7	1.4	0.49	Concrete, 1.4 m, normal lighting
	0.85 m	1.7	1.4	0.50	Concrete, 1.4 m, increased lighting
	0.85 m	1.7	1.4	0.49	Concrete, 1.4 m, normal lighting, handles
	0.85 m	1.7	0.7	0.52	Concrete, 0.7 m, normal lighting, handles
	0.85 m	1.7	0.7	0.50	Concrete, 0.7 m, normal lighting
	0.85 m	1.7	0.7	0.49	Concrete, 0.7 m, increased lighting
	0.85 m	1.7	1.4	0.46	Concrete, 1.4 m, normal lighting
	0.85 m	1.7	1.4	0.39	Concrete, 1.4 m, failed lighting
	0.85 m	1.7	1.4	0.45	Macadam, 1.4 m, ladder, normal lighting
	0.85 m	1.7	1.4	0.51	Macadam, 1.4 m, normal lighting
	0.85 m	1.7	1.4	0.50	Macadam, 1.4 m, increased lighting
	0.85 m	1.7	1.4	0.47	Macadam, 1.4 m, normal lighting, handles
	0.85 m	1.7	0.7	0.52	Macadam, 0.7 m, normal lighting, handles
	0.85 m	1.7	0.7	0.54	Macadam, 0.7 m, normal lighting
	0.85 m	1.7	0.7	0.53	Macadam, 0.7 m, increased lighting
	0.85 m	1.7	1.4	0.50	Macadam, 1.4 m, normal lighting
	0.85 m	1.7	1.4	0.50	Macadam, 1.4 m, failed lighting
Frantzich (2000)	~1 m	1.2	1.4	0.1-0.2	First evacuation
	~1 m	1.2	1.4	0.4-0.6	Second evacuation with same participants

Reference	Space	Width [m]	Height [m]	Flow [p/s]	Note
Oswald et al. (2008);	0.75 m	1.3	1.15	0.25	-
Oswald et al. (2005); Oswald et al. (2011)	Unlimited	1.3	0.65-1	0.9	-
Capote et al. (2012a); Capote et al. (2011, 2012b)	Unlimited	0.81	0	0.57	-
Galea et al. (2014); Galea et al. (2013)	Unlimited	-	0	0.86	Normal light, average of 4 trials with same participants
	Unlimited	-	0	0.87	Emergency light, average of 4 trials with same participants
Galea and Gwynne (2000)	Unlimited	-	0	0.08	Overturned, smoke
				0.15	Overturned, no smoke
Norén and Winér (2003)	Unlimited	1.07	0.30	1.00	One-storey intercity train
		1.07	0.30	0.68	
		1.37	0.50	0.95	
		1.27	0.30	0.79	Two-storey intercity train
		1.40	0.30	1.14	
		1.27	0.30	1.07	
		1.27	0.70	0.73	
		0.88	0.30	0.76	Local train
		0.77	0.30	0.74	
		0.73	0.30	0.48	
		1.27	0.30 / 0	0.72	
		1.27	0.30	0.44	
		0.90	0.30	0.54	Intern. train
		1.20	0	1.59	Metro train

[*] Derived values stem from the new analysis summarized in Table 5, and not the values presented in Paper IV.

Tunnel evacuation

In Paper III and IV of this thesis, experimental findings of peoples' behaviors, walking speed, and exit choice during evacuation in both non-smoke- and smoke-filled rail tunnels are presented. The findings of both experiments are summarized in this chapter. Prior to that summary, a number of previously conducted empirical studies are presented. A few of these were conducted in rail tunnel environments. However, a number of studies conducted in other settings are also included as they also add knowledge applicable to rail tunnels. An example of this is walking speed in smoke. Frantzich and Nilsson (2003, p. 62), for example, argue that data on walking speed in smoke generated in a road tunnel laboratory experiment is applicable to almost any other setting. Thus, by including these types of studies that are relevant in the light of the results presented in Paper III and IV, valuable and complementing information is provided.

Previous studies

The presentation of previously conducted studies can be divided into two categories: (1) movement in the tunnel, and (2) exit choice. This categorization is based on the content in the appended papers, which addressed these aspects particularly.

Movement in the tunnel

One of the few studies that examined human behavior and walking speed in rail tunnels in the field is the experiment by Frantzich (2000) that was presented in the previous chapter. Frantzich (2000) measured the participants' walking speeds in different areas of the tunnel, and the average walking speeds were found to vary between 0.7-1.4 m/s. These values can be compared to 0.8 m/s, which is an average estimate derived by Kynaston (1997) based on a number of evacuation exercises in the Hong Kong Metro in which people were escorted in rail tunnels. It is, however, unclear under which conditions these exercises were conducted.

In addition to the quantitative estimation of walking speed, Frantzich (2000) observed that many participants were bothered by the lack of lighting. This caused them to stumble and, furthermore, to hold each other's hands during the evacuation. However, the participants seem to have adapted to the environment, as walking speeds increased with the distance walked. Another interesting observation is that the participants seemed to adapt their speeds to the slowest walking individual of the group with which they evacuated.

Information about walking speeds in smoke-free rail tunnels have also been generated in a laboratory experiment in which the effect of the width of an elevated escape walkway was examined (Ahlfont & Vermina Lundström, 2012; Vermina Lundström, Ahlfont, & Nilsson, 2014). The experiment included a total of 72 participants, mainly students, of whom 48 took part in a series of scenarios that were run 3-5 times each. The experiments were conducted as group experiments, and the mean walking speeds were found to increase with increased walkway width. In general, walking speeds varied between 1.3-1.6 m/s.

The two studies mentioned above provide valuable information on walking speed in smoke-free rail tunnels. However, as smoke is likely to obscure vision in case of a rail tunnel fire, speeds can be expected to be lower compared to smoke-free environments. Despite the fact that research within the field of human behavior in fire quite early on demonstrated that it is not uncommon for evacuees to evacuate through smoke in case of fire (Bryan, 1977; Wood, 1972), few previous research studies have focused on this phenomenon. Furthermore, none of these were conducted in the setting of a rail tunnel environment, but in the absence of such studies they may still provide valuable information that can be used to complement the findings presented in this thesis. Unfortunately, the quality in terms of results presentation varies, and it is not always that individual walking speeds are explicitly presented as a function of visibility conditions, which in this thesis is represented by the extinction coefficient. Some examples do, however, exist.

One of the first research studies on walking speed in smoke was carried out by Jin (1976, 1978), who performed a laboratory evacuation experiment, in which 10 male participants were instructed to move through a 20 m long corridor filled with both irritant or non-irritant smoke. In the experiment, which represents the only recorded data related to walking speeds in irritant smoke, extinction coefficients varied between approximately 0.3-1.5 1/meter (m^{-1}). According to Jin (1976, 1978), the study demonstrated a negative correlation between walking speed and extinction coefficient. In other words, walking speeds decreased as smoke density increased.

The study by Jin (1976, 1978) was followed by a number of other studies confirming his findings (Akizuki, Yamao, & Tanaka, 2007; Boer & Withington, 2004; Frantzich & Nilsson, 2003, 2004; Heskestad, 1999; Jin, 1981; Jin & Yamada, 1989; Wright, Cook, & Webber, 2001). All of these were conducted as laboratory evacuation experiments, and the settings were typically made up by simple corridors, but examples of other settings, such as road tunnels, also exist. Often, the objectives were not only to examine walking speed in smoke, but also at the same time, to evaluate aspects related to way-finding and design of emergency exits. The studies are summarized in Table 7, in which details on the measured walking speed intervals and the corresponding extinction coefficient intervals, calculated with the natural logarithm, are presented. Also included are data from an experiment presented by Galea, Gwynne, Blackshields, Lawrence, and Filippidis (2001), which were reproduced from Xie (2011, p. 220).

As a complement to Table 7, the studies in which the individual walking speeds were presented as a function of the extinction coefficient are illustrated in Figure 10. When studying both Table 7 and Figure 10, it should be noted that each study is associated with a number of limitations that need to be emphasized in the interpretation of the data, particularly when comparing the results. These limitations may, furthermore, differ between the different experiments due to the setup, environment, participants, information given to the participants, etc.

Varying measurement techniques also need to be addressed when interpreting and comparing the data. Walking speeds may, for example, have been measured differently. In addition, a number of different techniques and equipment may have been used to estimate extinction coefficients. Different light sources do, for example, produce light with varying wavelengths, which affects the extinction of the light, and subsequently, the extinction measurements (Drysdale, 2011, pp. 448-449; Nilsson & Holmstedt, 2008, p. 67). Furthermore, extinction coefficients can be calculated and expressed differently, depending on whether or not the calculations are done with a natural logarithm or base-10 logarithm (Nilsson & Holmstedt, 2008). Unfortunately, most publications seldom explicitly describe how or where extinction measurements were done, or how extinction coefficients were calculated. Wright et al. (2001), for example, only report a mean extinction coefficient of 1.1 m^{-1}, but it is believed that this value has been derived using the base-10 logarithm. Had the calculation instead been done using the natural logarithm, the value would correspond to 2.5 m^{-1}.

In addition to the quantitative estimations of walking speeds in smoke, and subsequently derived relationships, the studies also managed to identify a number of important qualitative aspects. One such recurring observation is the importance of walls. More specifically, when visibility conditions have been low, people have been observed to follow the walls in order to facilitate movement and orientation (Boer & Withington, 2004; Frantzich & Nilsson, 2003, 2004; Jin, 1976, 1978). As a result, the installation of hand rails has been suggested in order to facilitate walking and increase speeds when evacuation in smoke can be expected. Similar installations, such as continuous tactile systems, have also been proposed by Paulsen (1994).

A number of studies have examined the relationship between smoke and lighting conditions. Jin (1976, 1978) could not identify any particular differences due to light levels, but his findings are contradicted by Frantzich and Nilsson (2003, 2004) who identified a statistical difference between walking speed in smoke in lit conditions compared to unlit. In addition, Wright et al. (2001) also observed that walking speeds seem to increase when appropriate way guidance systems were used, such as light strips mounted close to the floor.

Table 7. A summary of previously conducted evacuation experiments that studied the relationship between walking speed and visibility. WS and EC are denotations for walking speed and extinction coefficient respectively.

Reference	Setting	WS [m/s]	EC [m^{-1}]
Jin (1976, 1978)	Laboratory experiment in corridor	0.3-1.0	0.3-1.2
Jin and Yamada (1989)	Laboratory experiment in corridor	0.5-1.1	0.1-1.1
Heskestad (1999)	Laboratory experiment in corridor	0.2-0.5	Not presented
Wright et al. (2001)	Laboratory experiment in corridor	0.53-0.75	2.5*
Frantzich and Nilsson (2003, 2004)	Laboratory experiment in road tunnel	0.2-0.8	2.0-7.5
Boer and Withington (2004)	Laboratory experiment in road tunnel	0.38-0.83	Not presented
Akizuki et al. (2007)	Laboratory experiment in corridor	0.5-1.1	0.3-1.8
Xie (2011)	Laboratory experiment in corridor	0.80-1.25	0.23
		0.46-1.22	1.15
		0.29-1.02	2.30

*Value has been recalculated based on the natural logarithm.

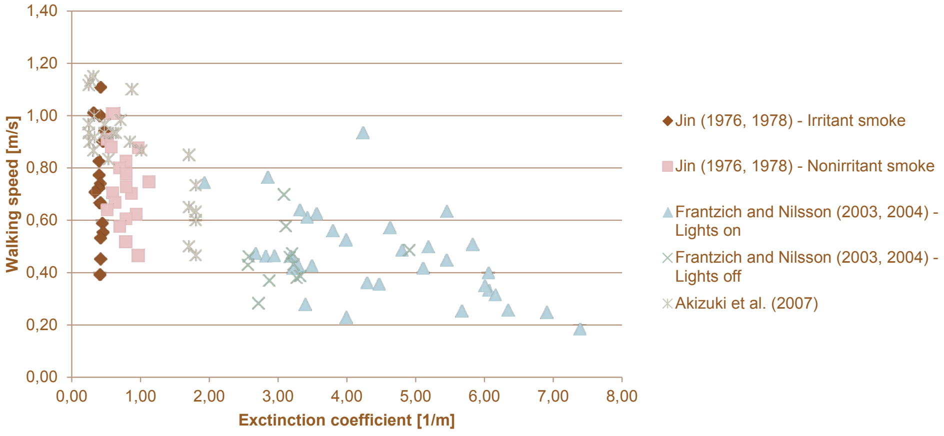

Figure 10. Individual walking speeds presented as a function of the extinction coefficient for a number of previously conducted studies in corridors and tunnel environments.

As illustrated by Table 7 and Figure 10, the ranges in which walking speeds have been found to vary are relatively wide, also within small extinction coefficient intervals. This is clear when studying, for example, the data by Jin (1976, 1978). Historically, these data sets have been represented by regression lines, which subsequently have been used to represent walking speed in smoke. Consulting all studies included in Figure 10 provides some support for this. However, it is not clear to what extent the results from different studies can be combined. Furthermore, it is not clear how differences between the studies affected the results, e.g., differences between the type of smoke and lighting conditions.

The fact that the data sets have been generated by adopting different research strategies causes implications also for application and design. Ronchi, Colonna, Gwynne, and Purser (2013) showed that the application of different data sets in egress models may yield different results when evacuation times are estimated. They also showed that the method of representing walking speed in smoke contributes to these differences, i.e., whether an individual's walking speed in smoke is represented as a fraction of the speed in clear conditions, or as an absolute reduction with no reference to the speed in clear conditions. Unfortunately, the previous studies provide little support on which of the representation methods is the most appropriate. This is because the walking speed of each individual was only examined for one specific extinction coefficient.

Exit choice

No known studies have explicitly examined emergency exit design in rail tunnels. In the absence of data for this specific environment, results generated during studies in buildings and in environments similar to rail tunnels, e.g., corridors and road tunnels, may be of considerable value. A number of studies have, for example, evaluated the importance of the size and the level of brightness of traditional emergency exit signs. The results from these studies indicate that the larger, brighter and more contrasting a sign is, the more conspicuous, i.e., easier to notice, it becomes (Fransson, 2008; Jin, Yamada, Kawai, & Takahashi, 1991; McClintock, Shields, Reinhardt-Rutland, & Leslie, 2001).

More sophisticated systems to aid way-finding have also been evaluated, and have been found to perform relatively well. McClintock et al. (2001), for example, conclude that by adding blue flashing lights to an emergency exit sign, i.e., an active evacuation system, its attention-capturing ability was increased. Laboratory experiments in corridors with students have generated similar results, and have shown that placing flashing lights or strobe lights next to an emergency exit sign increases the likelihood of the exit being noted (Nilsson, Frantzich, & Saunders, 2005).

Flashing lights especially have been used in both laboratory and field evacuation experiments in tunnel environments to increase the visibility and usage of emergency exits. Green lights have been recommended, partly because green relates to the associations of safety and go (Nilsson et al., 2005). The system was also demonstrated to aid the decision to evacuate in ambiguous situations (Nilsson, Frantzich, & Saunders, 2008). However, it has been hypothesized that the effectiveness of the system depends on the setting in which it is used. This can be illustrated by a laboratory evacuation experiment performed in a smoke-filled road tunnel (Frantzich & Nilsson, 2004). In the experiment, participants had to evacuate through a 37 m long tunnel which had been filled with artificial smoke with an irritant additive consisting of acetic acid. In total, three different types of systems to aid way finding were evaluated, including green flashing lights. The results illustrate some of the difficulties in attracting people to emergency exits during tunnel evacuation. In addition, the study demonstrated that getting people to notice an emergency exit in a tunnel is not the same as getting people to use it.

Another problem that affects the likelihood of a successful evacuation in rail tunnels is that emergency exits typically only are available on one side of the tunnel. As people tend to follow the walls during a tunnel evacuation, especially in smoke, alerting and attracting people to emergency exits on the opposite tunnel wall is important (Frantzich & Nilsson, 2004). As an alternative to active light installations at emergency exits, sound beacons have been demonstrated to increase exit usage when tested in an evacuation experiment in a smoke filled road tunnel (Boer & Withington, 2004). However, the applicability to rail tunnels is unknown as no studies have examined the effect in these settings.

Contribution

As was done in the above presentation on previously conducted research studies, the summary of the work presented in Paper III and IV is categorized into: (1) movement in the tunnel, and (2) exit choice. The aspects are covered both in Paper III and IV, with the main difference being that the participants taking part in the experiment presented in Paper III did so individually and in smoke. As a more detailed presentation of the laboratory evacuation experiment in Paper III has been presented published by Fridolf (2013), the summary is complemented with additional information also from this publication.

Movement in the tunnel

In Paper IV, the individual walking speeds observed in the field evacuation experiment are presented. On average, these speeds lie in the range of 1.1-1.2 m/s. It is, furthermore, concluded that the majority of the participants reduced their walking speed with increased distance walked. The average walking speeds are in line with the findings by Frantzich (2000). However, the results presented in Paper IV are more detailed and the variance in individual speeds is more transparently presented. This increases the applicability of the material to application and design usages, e.g., in performance-based design solution verification.

In previously conducted experiments, both in rail tunnels and other settings, people have been found to evacuate in groups (Delin & Norén, 2014; Fahy & Proulx, 2001; Frantzich, 2000; Heskestad, 1999; Norén, Delin, & Fridolf, 2014). It has also been argued that the individual walking speed is likely to be adapted to the slowest member of a group (Fahy & Proulx, 2001). Unfortunately, observations were only made at some locations in the rail tunnel, and it was not possible to provide a detailed description of whether people walked in groups or not in the field evacuation experiment. Still, it could be concluded that some people changed their position in order to walk beside slower-walking participants, just at the positions of where observations were done. More specifically, these participants stopped following the tunnel wall and walked out onto the rail tracks for a short while. The finding suggests that at least some people that are walking with a specific walking speed will try to maintain that speed, and also be able to do so if there is enough room on either or both sides of the slower individual in front.

In total, 27% of the participants explicitly mentioned that the coarse surface material in the rail tunnel, i.e., macadam, affected their ability to walk. The risk of tripping, and the fact that it was uncomfortable to walk on, were often mentioned as negative aspects. A few participants mentioned that they had adopted an alternative strategy to overcome this problem. More specifically, to walk on the concrete sleepers at the rail track. However, as the cameras in the tunnel only allowed observation at a number of specific points, it was not possible to quantify the potential effect on the walking speed.

As a complement to the results of individual walking speeds in a smoke-free rail tunnel presented in Paper IV, measurements of individual walking speeds in a smoke-filled rail tunnel were done in the laboratory experiment presented in Paper III. A distinction is made between a so-called movement speed and a so-called modelling speed. The main difference relates to how the different speeds were derived. The movement speed of each participant was derived by dividing the total distance walked in the tunnel by the time, i.e., excluding any stops that the participant made during the evacuation. The modelling speed was, on the other hand, derived by dividing the distance between the start and end position by the total time, including the duration of any stops. However, as can be seen in Paper III, the difference between the two types of speeds is negligible when presenting the average speeds of all participants. Possibly, this is due to the fact that only 25% of the participants stopped at some time during their evacuation. The average time stopped was also short, more specifically 14 s.

As can be seen in Paper III, the speeds are presented for different parts of the tunnel. In summary, all participants walked in the first part (a) of the tunnel, represented by a smooth floor material and a downhill gradient of 10%. Also, all participants walked in the second part (b) of the tunnel, which consisted of a smooth floor material and no gradient, see Figure 5. However, whether or not a participant walked on the third part (c) of the tunnel, which consisted of macadam and no gradient, depended on the initial position inside the tunnel at the beginning of the evacuation, and the participant's walking route. The results imply no practical differences in terms of average walking speeds between the different parts of the tunnel. This finding suggests that no differences would have been distinguishable, even if the gradient of the first part had been lower, and thus better conformed to the gradient of real railways. One possible explanation for the lack of difference is that neither the type of floor material nor inclination may determine the walking speed in environments that are as dark and obscured by smoke as in the laboratory evacuation experiment. In other words, the impact of these variables may be so trivial that the effect on the walking speed is not significant.

As no practical differences between the different parts of the tunnel was observed, it was deemed applicable to describe each participant's walking speed as an average number for the entire evacuation. By doing so, a more detailed presentation of the individual walking speed as a function of the extinction coefficient can be presented. This has been done by Fridolf (2013), and the data set has also been used by Fridolf et al. (2014) to provide recommendations on how designers should treat data on walking speed in smoke in fire-safety-risk assessments. To facilitate a comparison to previous studies, the data set is reproduced in Figure 11, and is also presented together with the findings of some previously conducted studies in Figure 18.

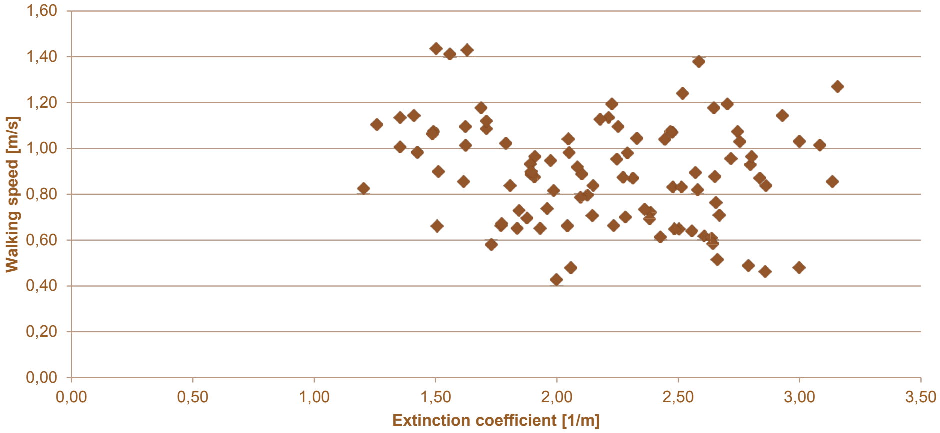

Figure 11. Individual walking speeds presented as a function of the extinction coefficient for the laboratory evacuation experiment.

Studying the individual data points, it becomes clear that the relationship often used to represent walking speed in smoke is, to say the least, questionable. This finding is, furthermore, supported by a later experiment in a smoke filled road tunnel (Fridolf & Frantzich, 2014, 2015; Fridolf, Frantzich, Ronchi, & Nilsson, 2015). In fact, it may be argued that a linear regression line, often used to represent the reduction of walking speed in smoke, is inappropriate due to the large variation in walking speeds in intervals with small extinction coefficients. Another alternative, in which a better prediction of individual walking speeds can be provided with a lower degree of uncertainty, has therefore, been presented by Fridolf et al. (2014).

In addition to the quantitative descriptions of the participants' walking speed in smoke, Paper III also provides details on how the participants moved and oriented themselves during the evacuation. For example, observations revealed that 91% of the participants followed one of the tunnel walls at least 75% of the total distance walked during the evacuation. Participants adopted this strategy as it facilitated both orientation and movement in the dark and smoke filled tunnel.

Another factor that aided the participants' orientation was small emergency lights, attached to emergency signs illustrating distances to the nearest exits, which was installed every 8 m on both tunnel walls. In total, 96% of the participants reported that they had seen the lights sometime during their evacuation. The participants perceived these emergency signs as extremely important as they did not only provide light to orient by, but also information on which to base decisions on way-finding. Some participants stated that this was comforting. It was also revealed that the participants of the laboratory evacuation experiment in the smoke-filled tunnel adopted different movement strategies. The most frequent strategies are presented in Paper III, together with various explanations of the choice of movement strategy given by the participants.

Based on their experiences gained in the evacuation experiment, the participants were asked about the most important design aspects of a solution, or any other technical aid, that would help them in a rail tunnel evacuation. A detailed summary of their answers is presented by Fridolf (2013). In particular, lighting and emergency signs similar to what was used in the experiment dominated the responses. Among other things, more and stronger lights were suggested, as well as shorter distances between emergency signs with light sources. Apart from lights and signs, suggestions for a handrail in the tunnel wall to assist movement dominated the answers. The participants did, for example, wish for something to hold onto, which could ensure that they were walking in the right direction and also that they were not approaching the rail tracks. Some participants also mentioned that such an installation would reduce the risk of gripping or touching something inappropriate, such as electrical wires. In addition, it was argued that a handrail would improve balance and increase walking speed on uneven surfaces.

A flat and even surface to walk on was also frequently suggested as a design improvement to increase perceived safety during rail tunnel evacuation. In addition, many participants also wanted the walkway to be better illuminated than in the laboratory evacuation experiment. Light strips, similar to those used in airplanes, were put forward as one suggestion, partly because it could light up the walking path but also because people then would not have to worry about walking on the rail tracks. A potential solution could be to provide rail tunnels with designated elevated escape walkways, as it would offer a smooth surface and signal to people where to walk, thereby reducing the uncertainty and fear about coming too close to electrical wires, rails, and the tracks. Thus, an elevated escape walkway may be beneficial not only in terms of increasing the ability to evacuate a train safely in a rail tunnel, but also in terms of facilitating movement in the tunnel.

Exit choice

In the laboratory evacuation experiment presented in Paper III, an emergency exit was installed 180 m into the tunnel on the left side of the direction of travel; see Figure 5. It was equipped with a number of way-finding installations, which were combined to give five different experiment scenarios, in order to study the effectiveness of each design in attracting people to the door. In total, six different installations were used, including: (1) a strong halogen lamp above the emergency exit; (2) a standard emergency exit sign above and on the lower part of the door; (3) two green flashing lights installed on each side of the emergency exit sign; (4) a loudspeaker installed above the door, which would broadcast a combined alarm signal and a pre-recorded voice message; (5) green continuous lights installed on each side of the door on the lower part of the frame, and; (6) white continuous lights installed on each side of the door on the lower part of the frame. Illustrations of the door, including the installations that were active in each scenario, are presented in Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16. In the figures, only the active installations have been highlighted, but it should be noted that the door was also painted in a grey color and the frame in a green color. A picture of the door is available in Paper III.

In Paper III, two important conclusions related to the exit design are presented. Firstly, it is concluded that the experiment demonstrated the importance of the design, in particular for those who were approaching the exit on the opposite side of the tunnel. In other words, that certain emergency exit designs performed better than others in terms of attracting the participants. Secondly, it is concluded that although an individual may actually see an emergency exit, there is no guarantee that this means the exit will be used.

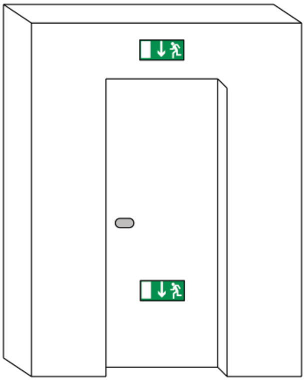

Figure 12. Scenario 1 with installation 2.

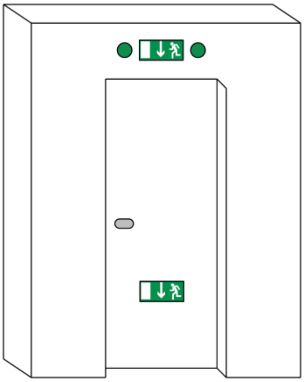

Figure 13. Scenario 2 with installation 2 and 3.

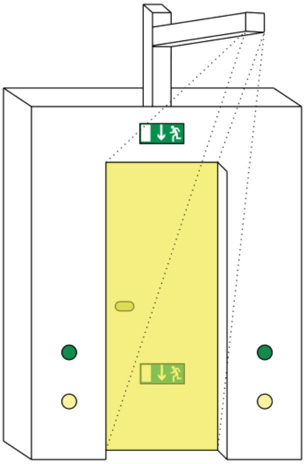

Figure 14. Scenario 3 with installation 1, 2, 5 and 6.

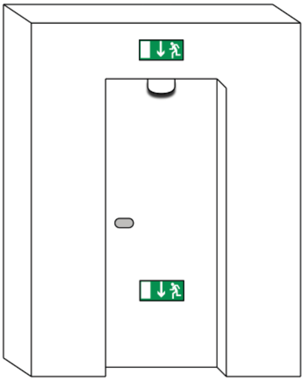

Figure 15. Scenario 4 with installation 2 and 4.

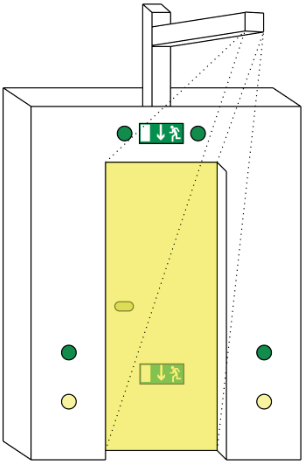

Figure 16. Scenario 5 with installation 1, 2, 3, 5, and 6.

Particular support for the first conclusion, i.e., that certain emergency exits perform better than others in terms of attracting participants, was provided by the emergency exit design used in scenario 4. In this scenario, a loudspeaker complemented the standard emergency exit sign above the door. The design generated a 100% usage of the exit, i.e., all 24 participants that took part in the scenario chose to exit there. A statistical analysis revealed that the exit used in scenario 4 was more frequently used by the participants walking on the right side of the tunnel compared to scenario 1 or 3, and when compared to scenarios 1,2, 3 and 5 altogether. A possible explanation for this is that it utilized a sense other than sight, which is traditionally exploited in life safety design. The introduction of sound, thus, provided participants with a stimulus, which was independent of the individual's capability to see.

Another positive aspect of the loudspeaker installation used in scenario 4, which is presented in Paper III, was revealed in an analysis of the participants' individual walking paths. A general problem noted in the other scenarios was that many participants who were approaching the exit on the opposite side of the tunnel noticed it too late, i.e., when they had already passed it. This caused them to turn back before crossing the tunnel section. However, in scenario 4, the majority of the participants who were walking on the opposite side began to adjust their walking direction and started to cross the tunnel relatively far from the exit. At approximately 8-24 m before the exit, they simply let go of the tunnel wall to cross the tunnel, which minimized the risk of passing the exit. A general illustration of the phenomenon is presented in Figure 17.

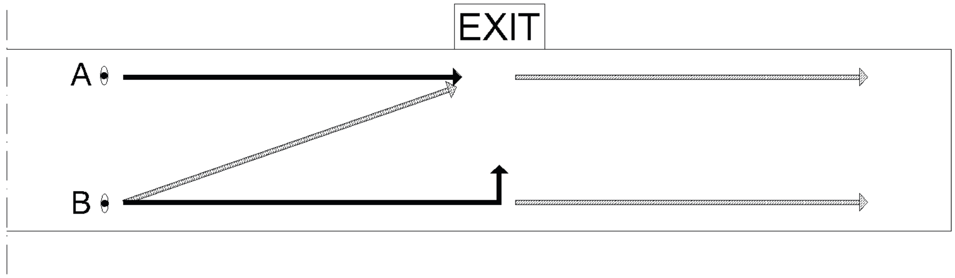

Figure 17. The participants taking part in scenario 4 of the laboratory evacuation experiment redirected their walking route earlier than the participants in any other scenario. This is illustrated by the grey arrow between position B and the emergency exit.

Support for the second conclusion, i.e., that noticing an emergency exit is not the same as deciding to use it, was provided in a number of interviews with the participants who took part, especially in scenario 3. During the interviews, in which the participants watched the video recording of their evacuation, it was revealed that the emergency exit had been interpreted as the front of a train. Most likely, this was due to the obscuration by smoke, and it introduced an uncertainty related to the decision to walk to the emergency exit or not. Similar statements were provided by some participants who took part in scenario 2. Although green flashing lights seem to have contributed to the higher usage of the emergency exit compared to scenario 1, a number of participants misinterpreted the meaning of the flashing lights. One participant, for example, interpreted the flashing lights as a rail switch and another related it to a traffic signal.

The laboratory experiment presented in Paper III thus managed to identify an important relationship between the emergency exit design and the awareness and usage of that exit. As the emergency exit design used in scenario 4 was found to perform particularly well, it was selected for the field evacuation experiment in the Stockholm Metro, presented in Paper IV. In this experiment, no smoke was present and the experiment was performed by a group of 135 participants.

In Paper IV, it is concluded that all 135 participants found, and also used the emergency exit to make their way out of the tunnel. Naturally, this is a good outcome and again demonstrates the potential of the emergency exit design including a loudspeaker. However, it is also stated in Paper IV that as few as 10% of the participants reported that they had noticed the emergency exit by sound. In contrast, signs and social influence were more frequently stated as reasons why a certain participant had become aware of the exit. Furthermore, approximately 60% of the participants stated that their exit choice was dictated by the decisions or actions of others.

Thus, although all participants used the emergency exit, the reason for doing so may to a greater extent be related to the influence of others, e.g., participants walking in front, than the design itself. This is likely to have a large effect on the outcome of a rail tunnel evacuation, in which many people are involved. However, it is also argued in Paper IV that although the influence of others is likely to have a large effect on exit choice, the value of a proper exit design is important for the first individual(s) reaching the exit. The reason is simply that if the exit design fails in attracting the first people to it, it is more likely that the people following them will also decide not to use the exit. Similar observations have, for example, been made by Frantzich et al. (2007) in a road tunnel evacuation experiment. Consequently, a poor exit design may increase the risk that people will walk unnecessary long distances in order to reach a safe location during a rail tunnel evacuation.

Summary

The laboratory evacuation experiment generated a comprehensive data set on walking speed in smoke, which has been presented in Paper III and in a related publication by the author (Fridolf, 2013). The data set is presented in Figure 18 together with a number of previous studies. Paper III also provides valuable information on typical behaviors during evacuation in smoke. It is concluded that other senses, such as touch and hearing, are employed to a higher degree when vision is reduced. The finding is in line with previous studies (Boer & Withington, 2004; Frantzich & Nilsson, 2003, 2004; Jin, 1976, 1978). As a complement to the data set on walking speeds in smoke, Paper IV also provides detailed information on rail tunnel walking speeds when no smoke is present. These speeds were presented as averaged values complemented with a standard deviation, which facilitates the treatment of uncertainties in application and design.

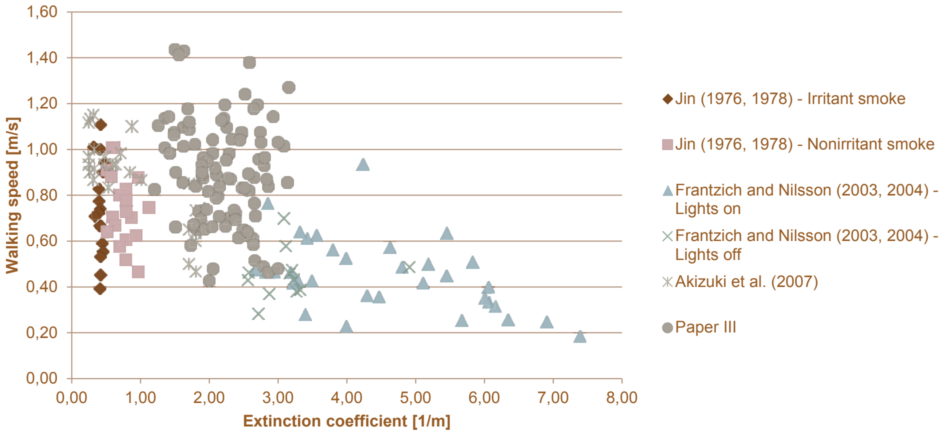

Figure 18. A combined presentation of the individual walking speeds derived in previous studies and the laboratory evacuation experiment presented in Paper III.

In both Paper III and IV, it is concluded that the emergency exit design with a loudspeaker, enabling an alarm signal and a pre-recorded voice message to be broadcasted, was effective in terms of notifying people about the exit, and also in terms of getting people to use it. A similar solution was tested in a road tunnel by Boer and Withington (2004). However, in the present studies, the design generated a significantly better response. Possibly, this was due to the combination of an alarm signal and a spoken message, which provided the participants with a stimulus intended for a sense other than sight. Different combinations of light installations, however, were not as effective in terms of exit usage in some occasions. Although they made participants aware of the exit, misinterpretations were not uncommon when smoke was present.

Application and design

For many reasons, rail tunnel evacuation due to fire is a highly unwanted event. Fortunately, it rarely occurs. Unfortunately, when it does occur, it often leads to devastating consequences in terms of lives lost and injuries. As was pointed out in the introduction to this thesis, a crucial aspect of the fire safety level of a rail tunnel is the possibility of a safe escape. Consequently, design solutions and safety concepts in rail tunnels need to support the likely behavior patterns of the people occupying them. This requires applicable information and data, both qualitative and quantitative, on human behavior in rail tunnel fires. One of the main contributions of this thesis is that it not only provides new information and data on the topic, but that it also provides an extensive overview of the current knowledge in the field. Thus, the thesis can be used to reduce the current uncertainties in numerous applications. Yet, little has been said on how the information and data can be used in application and design.

As demonstrated in Paper I, the theoretical framework can assist in the analysis of past rail tunnel fires. The applicability of the framework to these types of facilities is not only demonstrated by Paper I, but also by a number of previously conducted research studies. By adopting the framework, an accident investigator can use a structured method for identifying typical behaviors and to reach valid conclusions about the events that have occurred. Subsequently, the framework facilitates learning about peoples' behavior in previous fire accidents, and this is of great importance if future, similar accidents are to be prevented (Beale, 2002). The framework may possibly also be used not only to analyze major accidents, but also minor incidents which ended well. In particular, the identification of behaviors that have prevented minor incidents from becoming major accidents is important, as it may lead to conclusions and knowledge that are not obtainable from major accidents (Bodart et al., 2004). This knowledge may, furthermore, be used to design safety systems that promote as many of the identified appropriate behaviors as possible.

Another positive aspect of the adoption of a clear theoretical framework in the review of past fire incidents is that it may provide new insights into peoples' behavior (Eder, Bruttin, Muhlberger, & Pauli, 2009, p. 607). Furthermore, it allows human behavior in fire to be described without the use of the term "panic". Although this is a term frequently used, today it is considered a myth within the research community, and has been since the 1970s, simply because there is little evidence of panic behavior in past fires (Fahy, Proulx, & Aiman, 2009; Sime, 1980). On the contrary, typical behaviors in fires appear rational when studied in relation to context of the situation. Such studies are essentially facilitated by a clear theoretical framework.

The adoption of a clear theoretical framework can also greatly aid fire safety designers of underground rail transportation systems, in general, and rail tunnels, in particular. Typically, fire safety designers utilize egress time-line models in the performance-based solution design verification process (Proulx, 2008b). Although these models are very valuable in quantifying evacuation processes, egress-time line models are to be considered as relatively basic engineering tools. Consequently, they provide little understanding of human behavior in fire. The adoption of a theoretical framework for human behavior in fire may, however, provide this type of guidance. The framework can, for example, help a designer develop solutions that support people in case of fire, i.e., with qualitative aspects. By complementing the egress time-line model with the framework in order to predict particular behaviors in a rail tunnel fire, better solutions may be adopted, and subsequently, a higher safety level can be achieved. In addition, the adoption of a theoretical framework may also provide guidance on, for example, initial behaviors or interactions among people, which can facilitate quantification of time spent on so-called pre-evacuation activities.

The theoretical framework is also likely to be beneficial for operators of rail tunnels, e.g., metro operators, as well as fire rescue services. Operators should, for example, take advantage of the authority role that their staff is likely to have, which can be understood by consulting the role-rule model. Similarly, rescue services may guide their training and operation so that they know what to expect, and can take advantage of the likely behavior of people in case of a rail tunnel fire. The theoretical framework can, however, not be used to describe the exact patterns of peoples' behavior during rail tunnel evacuation due to fire, but rather general behaviors of average individuals.

Another problem is that the theoretical framework cannot be used to assess total evacuation times. This, however, is often required when the fire safety design of a rail tunnel is evaluated using engineering analyses. In quantitative analyses, for example, the performance of the fire safety design of a rail tunnel is evaluated by the analysis of a number of representative fire scenarios in that tunnel (ISO, 2011; SFPE, 2006, 2007). Typically, the analysis includes the assessment of the available safe escape time (ASET), and the required safe escape time (RSET) for each scenario, according to the egress time model (Proulx, 2008a). When the engineer verifies that the proposed fire safety design delivers a sufficient level of safety, he/she can do so by assessing the ASET and the RSET more or less independent of each other. However, a more complex approach can also be adopted in which the engineer, for example, compares the accumulated dose of toxicants in the body with the effective dose to cause irritation, incapacitation, or death, according to the fractional effective dose concept (Purser, 2008, 2009).

Independent of engineering approach, the engineer must demonstrate that the self-rescue principle is fulfilled, i.e., that people in a rail tunnel fire are able to evacuate to a safe place before untenable conditions occur. Although an old and general rule is to move passenger trains on fire to a safe place, either out of the tunnel or to the nearest station, and to disembark its passengers there, the performance-based design solution verification should also include one or more scenarios in which the train is evacuated in the tunnel. This is because there is no guarantee that a train can move to the safe location in case of a rail tunnel fire, as this can only occur when the train has not been disabled, and when there are no other trains blocking the tracks.

Thus, if a designer is to be able to verify that the proposed fire safety design of a rail tunnel delivers a sufficient level of safety, information and data on different parts of the evacuation process are required; this applies also for train evacuation in the tunnel. As an example, quantitative data on flow rate capacities at train exits are required in order to estimate the time it will take to empty a train. In addition, information on walking speeds is important for estimations of travelling times to safe locations. This information is provided by Paper II-IV, but also in a number of previous studies which have been summarized in this thesis.

When a designer uses the results from an empirical research study, consideration must be given to how the data should be interpreted. In this perspective, it is necessary to evaluate the quality of the data. This can be done, to some extent, by evaluating the validity and reliability of the research results, but the evaluation must also be complemented by an assessment of how, and to what extent, the data can be used for prediction purposes. This is particularly true for data which by their very nature are descriptive, such as the data on flow rate capacities and walking speeds presented in Paper II-IV. Although the data have been collected in specific settings, this does not prohibit it from being used for generalization in a setting beyond that studied (Holme & Solvang, 1997, p. 304; Robson, 2011, p. 160). However, when such data are used for prediction purposes in application and design, for example, to estimate the RSET, a dimension of uncertainty is added to the data.

How to treat this uncertainty depends on the complexity of the fire risk analysis method that is adopted to verify that the proposed fire safety design delivers a sufficient level of safety. In other words, performance-based design solution verification can make use of a range of methods, depending on how the designer chooses to manage the inherent uncertainty in the design (Paté-Cornell, 1996). Two approaches that are often used are deterministic analysis and quantitative risk analysis (QRA) (Frantzich, 1998, pp. 9-11). In the deterministic analysis, also known as scenario analysis, a manageable number of fire and evacuation scenarios are selected that represent worst credible cases. They are then analyzed, and a comparison of the ASET and the RSET is done for each case. In the deterministic analysis, the hazards are mainly described in terms of their consequences, and the designer must use descriptive data so that the result is considered conservative. More specifically, the designer should choose data in such a way that the probability of obtaining a situation worse than the representative scenario is small. By doing so, the uncertainty in the data is implicitly considered. In contrast to the deterministic analysis, a QRA represents a likely description of the consequences with consideration given to the frequency for each scenario. The inherent uncertainty is, thus, considered by the number of scenarios and their representation in terms of both frequency and consequence. In other words, the inherent uncertainty in the data is explicitly managed as separate scenarios.

This means that the basic data set employed can be the same regardless of the method used to verify the performance-based design solution. However, depending on how the designer decides to manage the uncertainties, either a lower percentile representing a conservative value, or an average value in combination with the variability of the data, is selected. The main benefit of the data presented in Paper II-IV, compared to many of the previously conducted empirical studies on rail tunnel evacuation, is that the data are presented with a high level of detail. More specifically, the data are presented as average numbers with a transparent description of the variability in the data. This facilitates the data being employed in application and design, regardless of the fire risk analysis method adopted by the designer.

The contribution by Paper II-IV, however, extends beyond the mere quantitative data sets. In particular, Paper III and IV provide essential information that can be used not only to describe, but also to explain, some of the behaviors observed in the different experiments. This information can be used to design both trains and rail tunnels so as to facilitate evacuation. Furthermore, train and tunnel operators and owners can utilize the information to develop and incorporate safety concepts that make use of general behaviors observed in empirical studies, both the ones included in this thesis and those in previously conducted studies. This relates, for example, to the strategies adopted by people to move about and orient themselves in dark and potentially smoke-filled tunnels. By considering these aspects when evaluating different designs, it is likely that the risk to people caught in a rail tunnel fire would be reduced.

A good example of this is the design of the emergency exit which was used both in the laboratory evacuation experiment presented in Paper III, and the field evacuation experiment presented in Paper IV. The experiments demonstrated that an emergency exit which is equipped with a loudspeaker installation that permits both an alarm signal and a spoken message to be broadcast may be particularly effective in terms of guiding people to safety. The experiments also demonstrated that other exit designs were not as effective. In fact, some even caused people not to use the exit. It is also recognized that the exit design with the loudspeaker installation may not necessarily be an effective design in buildings above ground, partly because the number of walking routes and available exits may be many, which can cause the sound from one exit to interfere with that from another. In contrast, distances between safe locations in a rail tunnel are typically very long and emergency exits may only exist on one side of the tunnel.

Consequently, a design that is not preferable in one building type may be so in another. This illustrates the importance of considering and evaluating design aspects in relation to the context within which the design will be used, and furthermore, of testing them in a systematic manner. Nilsson (2009) presented a research strategy that may be used to facilitate this process, in which he utilizes a theoretical framework termed the theory of affordances (Gibson, 1977; Hartson, 2003). An example which applies the strategy in the setting of underground transportation systems was, furthermore, presented by Nilsson, Fridolf, and Frantzich (2012). It is recommended that similar strategies be adopted by train and rail tunnel owners, as well as designers, in order to increase the use of appropriate evacuation systems.

Conclusions

This thesis expands the current knowledge on rail tunnel evacuation by the contribution of new data, which can be integrated with the findings of previous research studies. The most important findings of the contribution presented in this thesis are summarized below.

In relation to research objective 1, a theoretical framework, including four generally accepted theories and models that can facilitate the understanding of human behavior in fire, has been identified, and its applicability to rail tunnel evacuation demonstrated. The adoption of such a framework is likely to be beneficial to fire investigators, rail tunnel owners and operators, fire safety designers, and fire rescue services. It can, for example, be used to describe the behavior in past rail tunnel fires or to predict general behavior patterns of average individuals in the future.

In relation to research objective 2a, new data on the flow rate capacity of train exits during evacuation in rail tunnels with limited lateral space have been presented. The presentation includes a transparent description of the variability in the data which facilitates their utilization in application and design. The most important findings are that:

- Average flow rates varied between 0.17-0.21 p/s during a field evacuation experiment in the Stockholm Metro.
- Significantly higher flow rates were observed during a laboratory evacuation experiment, including only young and healthy students. On average, flow rates were in the order of 0.5 p/s. Different train exit configurations had little practical effect on the flow rate of people.
- Perceived difficulties to exiting a train in a rail tunnel were typically expressed to be associated with the height difference between the train and tunnel floor, and crowding or obstruction by other people in the tunnel.

In relation to research objective 2b, new data on walking speeds in smoke free and smoke filled rail tunnels have been presented. The presentation includes a transparent description of the variability in the data, which facilitates their utilization in application and design. The most important conclusions are that:

- Average individual walking speeds varied between 1.1-1.2 m/s during a field evacuation experiment in the Stockholm Metro.

- Lower walking speeds were observed in a laboratory evacuation experiment when smoke was introduced. On average, walking speeds were in the order of 0.9 m/s, but varied significantly between 0.4-1.8 m/s within an extinction coefficient interval of between approximately 1-3 m^{-1}. No clear correlation between walking speed and extinction coefficient was identified.
- People followed the tunnel walls in both experiments. When smoke was introduced, many people walked with their hands in front of the body or on the tunnel wall.

In relation to research objective 3, a number of technical installations to facilitate orientation and movement, and to aid way-finding in rail tunnels have been presented. The most important conclusions are that:

- Continuous emergency exit signs, including a light installation and information about distances to the closest exits, were shown to be particularly effective in terms of orientation and way-finding during rail tunnel evacuation in smoke.
- An emergency exit equipped with a loudspeaker installation that permits both an alarm signal and a spoken message to be broadcast was shown to be particularly effective in terms of guiding people to safety, both during rail tunnel evacuation in smoke-filled and smoke-free environments.

Future research

Although this thesis contributes with new information and data that expands the current knowledge on rail tunnel evacuation in case of fire, it also shows that there is room for future research within the field. A number of suggestions for future research are presented below.

People with disabilities

Today, it is becoming more and more expected that everyone should have access to the same services in society. For example, the transportation system, including rail tunnels, shall be designed so that anyone can use them, regardless of disability. This is clearly stated in the ninth article of the Convention on the Rights of Persons with Disabilities, which was adopted by the United Nations General Assembly on December 13, 2006 (UN General Assembly, 2006). Thus, efforts have been made by all State Parties that have signed the convention to make underground rail transportation systems also more accessible. However, the same level of attention has not been directed to safety aspects. More specifically, it has not been considered how to ensure that vulnerable people, e.g., people with disabilities and the elderly, can safely be evacuated in case of fire. This thesis is no exception.

A delimitation of most of the findings presented is that they are only applicable for an able-bodied population. Still, much of what is presented in this thesis can be discussed in the light of a vulnerable population. It can, for example, be expected that people with disabilities and senior citizens will have particular difficulties evacuating a train by overcoming the height difference between the train and tunnel floor (Fridolf et al., 2012). Furthermore, people with disabilities and elderly may experience severe problems during a rail tunnel evacuation, for example, on an uneven surface material. Consequently, future research should strive to find technical solutions and methods to encourage and maintain sustainable rail tunnels. This means not only focusing on accessibility, but also on egress ability for vulnerable people, such as people with disabilities and senior citizens.

Elevated escape walkways

In the experiments presented in this thesis, and in a number of previously conducted research studies, participants have perceived difficulties in exiting trains in rail tunnels due to the height difference between the train and tunnel floor. One possible solution to increase the ability to safely exit a train during a rail tunnel evacuation involves emergency ladders, which in Paper IV was mentioned by many participants. However, emergency ladders were also shown to decrease the flow rate capacity of a train exit. In addition, emergency ladders have been shown to obstruct the already limited lateral space between the train and the tunnel wall during rail tunnel evacuation. Thus, it is not entirely clear that emergency ladders always are an appropriate aid.

Based on the findings of this thesis, it is also evident that many people feel insecure while walking in dark and smoke-filled tunnels. Due to a fear of colliding with obstacles, and touching electrical wires or the electrical rail used to motorize trains, many participants walked slowly, close to the walls, sometimes bent over and/or with their hands up for protection. One potential solution, which may also serve as an alternative to an emergency ladder, could be to provide rail tunnels with designated walkways raised above track level. This would possibly signal to evacuees where to walk during a rail tunnel evacuation. Furthermore, such a designated walkway would also allow for people to walk on a solid, even surface, making it easier especially for people with movement disabilities, senior citizens, and children. In addition, if it were raised above track level, the walkway would likely facilitate evacuation of the train, particularly for the vulnerable groups mentioned above.

Obviously, there may be many benefits of an elevated escape walkway during a rail tunnel evacuation. However, as the empirical data are scarce, it is suggested that:

1. The results generated by Ahlfont and Vermina Lundström (2012) and Vermina Lundström et al. (2014) be verified in field settings with a more representative sample of participants, i.e., not only students. This should include studying also the behavior of people along the elevated walkway, i.e., if people will adapt their walking speed to the slowest individual, or try to pass each other in order to maintain their preferred walking speeds.
2. A more detailed examination of how an elevated walkway would affect the overall flow rate capacity of train exits be carried out, as it is not entirely clear that average flow rates would increase significantly, other than in the initial events of the evacuation. This is because the limited lateral space offered by a raised platform may become heavily congested.

Walking speed in smoke

One of the major contributions of this thesis is the new information, i.e., the data set, on individual walking speeds in smoke. Still, data on individual walking speeds in smoke are scarce. In addition, this thesis demonstrates that the variation in walking speed within individual studies is large, and that findings from different studies also vary. Although the studies indicate that the level of smoke density may have a negative impact on walking speed, it is not clear that relationships commonly used for representing walking speed in smoke are appropriate. In fact, it may be argued that a linear regression line, often used to represent the reduction in walking speed in smoke, is inappropriate due to the large variation in walking speeds in small extinction coefficient intervals (Fridolf et al., 2014).

As the studies that have examined walking speed in smoke most often have included few participants, it would be good if such findings could be combined in order to allow making more general conclusions on how to represent walking speed in smoke. However, a problem is that there are significant differences between these studies. Among other things, the following aspects vary between the studies: the type of environment in which the experiment were carried out, the type of smoke that was used, the distance evacuated by the participants, the presence or absence of physical barriers, e.g., cars, the type of information provided to the participants prior to the evacuation, etc. Furthermore, it is not always explicitly stated how walking speeds and extinction coefficients were derived.

Another problem which makes it difficult to draw conclusions on how individual walking speeds are affected by smoke and visibility conditions is the fact that the current data sets have examined only the walking speed of each individual for one specific extinction coefficient. In other words, it is difficult to predict how a certain individual's walking speed will vary as a function of different extinction coefficients. Still, it is common today to represent an individual's walking speed in smoke as a fractional reduction of the unimpeded walking speed (Ronchi et al., 2013; Xie, 2011). This approach implies that there is a relationship between an individual's ability to walk in smoke, and his/her unimpeded walking speed. Yet, it is not possible to draw such a conclusion based on the currently available research studies. For that reason, empirical data in which the same participants have walked in a number of different visibility intervals are required.

Obviously, many questions need to be addressed in relation to how movement is affected by smoke. It is suggested therefore that future research:

1. Search and review the current existing data on walking speed in smoke, and clarify whether and how findings from different empirical studies can be combined to provide more generalizable recommendations on how to represent walking speed in smoke in application and design. This should

include an examination of how extinction coefficient measurements may vary, both when different types of smoke are used, and when different types of light sources to measure extinction are used.

2. Collect new data on walking speed in smoke, preferably by measuring each participant's walking speed for different extinction coefficients as well as in clear conditions. Until this is done, no valid conclusions on how to represent an individual's walking speed in smoke can be drawn.
3. Examine the effect of different types of smoke on walking speed, including aspects such as color, smell, and level of irritation, and the potential consequences these variables may have on how people perceive their environment, e.g., contrasts of walls and signage.

Information and design

Lighting, signage, and similar technical solutions to aid way-finding have been demonstrated in this thesis to be important during rail tunnel evacuation, both to facilitate orientation and movement. It is recommended that future research continue to pursue solutions and aids that can assist people during rail tunnel evacuation, both in smoke-free and smoke-filled tunnel environments. In particular, it is recommended that future research should:

1. Examine the potential effects of different design solutions on rail tunnel walking speeds. As an example, hand rails and similar tactile markers are likely to help people during a rail tunnel evacuation. However, the extent to which such installations will contribute to faster walking speeds is unknown.
2. Identify new solutions on how to attract people that are walking on "the wrong side" of the tunnel, i.e., on the side of the tunnel opposite to the emergency exit.

Data from real situations

In this thesis, past rail tunnel fires have been examined in general using a case study method, which has resulted in qualitative knowledge. In contrast, empirical studies which adopted an experiment method have, in general, contributed with quantitative findings. It is acknowledged, however, that experiments always are associated, to a varying degree with a lack of realism. Typically, the problem is greater in a laboratory experiment than in field experiments, but it is always an aspect that, to some extent, is reflected in the data. This is because every experiment is an attempt to artificially describe a real world phenomenon, which means that it represents a more or less simplified version of a certain real world situation. Consequently, there are always consequences for the external validity, i.e., the extent to which the findings can be generalized.

An appealing alternative to the experiment method would be to utilize the case study method also in the collection of quantitative data during rail tunnel evacuations. Such investigations could, for example, not only be deployed after catastrophic accidents, or even fires, but also after minor incidents that required a train to be evacuated in a tunnel. Compared to most past investigations, such data collection would require a more detailed analysis of the evacuation. It may, however, be facilitated by the increased use of monitoring and video surveillance systems, which today typically are installed both onboard trains and in rail tunnels for other reasons.

By utilizing surveillance systems, generalizable data from real world situations could be provided at the cost of reduced control of peripheral variables and increased measurement uncertainties. A number of ethical issues also need to be addressed, as this option would involve using surveillance systems for purposes other than that for which they were originally installed. Still, results from such studies could complement findings generated in experiments, for example. It could also significantly contribute to more generalizable data, as well as an improved understanding of behaviors during a rail tunnel evacuation. It is, therefore, recommended that future research explore the potential of collecting data on rail tunnel evacuation and behaviors during such events, even if they were minor and not necessarily initiated by a fire.

Concluding remarks

As stated in the introduction to this thesis, engineering principles have developed greatly since the construction of the Nyboda rail tunnel in Sweden, which opened more than 150 years ago. Rail tunnels today can be substantially longer, located far deeper underground, and be part of large underground rail transportation systems with many tunnels and vital societal functions. Obviously, this has introduced new fire and life-safety challenges that need to be considered both during the design of new rail tunnels, and the operation of those already existing. This thesis provides knowledge that can be used to meet some of these challenges. It is also acknowledged, particularly by the discussion in this chapter, that the efforts should not stop at this thesis and that much important work lies ahead also in the future as engineering principles in other fields continue to develop.

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Rail Tunnel Evacuation

Rail tunnel fires are rare, but can lead to disastrous consequences in terms of lives lost and injured people. This is particularly true when passenger trains, in case of fire, cannot transport people to a safe location, but instead have to be evacuated in the tunnel. Consequently, a crucial safety-related aspect of a rail tunnel is the possibility of a safe escape. In order to avoid devastating accidents in the future, it is therefore necessary to consider human behavior aspect both during design and operation of rail tunnels, particularly information and data about human behavior in rail tunnel fires. Unfortunately, this type of information has, until now, been scarce. The objective of this thesis is, therefore, to increase the knowledge on rail tunnel evacuation in case of fire.

The thesis explores rail tunnel evacuation, and descriptive knowledge is presented related to the evacuation of passenger trains, and the subsequent tunnel evacuation to a safe location. More specifically, a theoretical framework that can aid the understanding of human behavior is identified, and its applicability to rail tunnels is demonstrated. In addition, new empirical data on the flow rate capacity of train exits during evacuation in rail tunnels, as well as on walking speeds in smoke free and smoke filled rail tunnels, is presented. Finally, a number of technical installations that may facilitate orientation, movement and exit choice in rail tunnels are suggested. The findings are presented in relation to previously conducted empirical studies, and a discussion is also made on how the findings can be used in application and design.

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