Modelling Crowd Evacuation from Road and Train Tunnels - Data and design for faster evacuations

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Abstract
The aim of this report is to present conclusions about factors of great importance for the evacuation efficiency from underground spaces such as road or train tunnels. Quantified information about the duration of different stages in the evacuation process is presented as well as conclusions about means to fasten the evacuation process. Of special interest from a risk management perspective is the role of the control room which therefore is analysed separately.

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SUMMARY

Focusing on tunnel safety from a risk management perspective the purpose of this report is to analyse the factors that affect the efficiency of crowd evacuations from road and train tunnels. These factors are analysed from two perspectives; first evacuation efficiency from the tunnel users' perspective is studied, then the tunnel control room is analysed.

The purpose of the first part of the study is to quantify the evacuation of people from underground spaces such as road or train tunnels. Quantifying the evacuation process makes it possible to compare the evacuation time to the time until critical conditions appear inside the tunnel. Furthermore, quantified information about the evacuation process is important when analysing the effect of different means on the duration of the evacuation process.

The purpose of the study of the control room is to see how different ways to organise the work correspond to the tasks of the control room. As the actions taken in the control room directly affect the course of events inside the tunnel it is important to study how the staff should be organised to be as efficient as possible.

To study the evacuation from road tunnels evacuation tests were undertaken in the Benelux tunnel in the Netherlands. In total nine groups of about 50 motorists stopped in the tunnel behind a smoking truck and their behaviour was recorded on video. To collect supplementary information for the evacuation from train tunnels several video recordings of people disembarking from different types of trains were made. Based on a three-stage model of the human behaviour of people facing accidents in tunnels the video material was analysed and the duration of the different stages for every individual was determined.

The control rooms of the Ij- and Piet Hein-tunnel and the Öresund link were visited and the daily work as well as the role during incidents were analysed.

The statistical analyses of the information showed that the evacuation process can be divided into three stages with statistically proven distributions. The study also revealed the dependence on the evacuation time of different factors, e.g. the group behaviour, the time until announcements are made via loudspeakers, the type of train in evacuations from trains, et cetera. Depending of the organisational approach of the control room information to the people inside the tunnel can be expected at different times.

Recommendations about actions that provide a faster evacuation process can be given based on the conclusions from the experimental tests and comparisons between these conclusions and findings presented from reports published earlier (see Chapter 2). The conclusion from the road tunnel tests is that the announcements given via the loudspeakers are what make most people decide to evacuate. Providing information as early as possible helps people decide what to do and makes people react at an earlier stage.

The group behaviour among the people in the road tunnel experiments was found to play a great role in the evacuation. This is not only a fascinating fact but also something that should be kept in mind when planning for evacuations. Bottlenecks appeared in front of the tunnel emergency exits in several of the road tunnel tests. This is clear evidence that there should either be more exits in the tunnel or that they should be designed to allow a faster flow. The vertical distance between the platform and the train floor level was shown to affect the flow through train doors in a large extent. The lesser the distance, the faster the flow will be.

SAMMANFATTNING

Syftet med den genomförda studien är att ur ett övergripande riskhanteringsperspektiv analysera de faktorer som har en avgörande betydelse för evakueringen från väg- och tågtunnlar. Dessa faktorer har analyserats från två perspektiv; först har evakuering av tunnlar studerats ur tunnelanvändarens perspektiv, därefter har kontrollrummets funktion analyserats.

I den första delen av studien är målet att ta fram kvantitativ data om evakuering av personer från underjordsutrymmen såsom väg- och järnvägstunnlar. Kvantitativ information om evakuering möjliggör en jämförelse mellan evakueringstiden och den tid det tar tills kritiska förhållanden uppstår. Dessutom är kvantitativ information av stor vikt vid analyser av olika åtgärders effekt när det gäller att minska evakueringstiden.

Syftet med studien av kontrollrummets funktion är att se hur olika sätt att organisera arbetet i kontrollrummet motsvarar de uppgifter som kontrollrummet förväntas kunna lösa. Eftersom de åtgärder som kontrollrummet svarar för har en direkt påverkan på händelseförloppet i tunneln är det av stor vikt att analysera hur arbetet i kontrollrummet skall vara organiserat för att vara så effektivt som möjligt.

För att studera evakuering från vägtunnlar har tester genomförts i Beneluxtunneln i Nederländerna. Sammanlagt nio grupper om vardera 50 personer deltog i testerna där personbilar tvingades stanna i en tunnel bakom en rykande lastbil. Förarnas beteende spelades in på videoband för att kunna analyseras. Videoinspelningar av personer som går ut från tågvagnar har även gjorts, detta för att kunna utvidga studien till att omfatta utrymning från tågtunnlar. Videomaterialet från de olika försöken har analyserats och utvärderats enligt en modell över mänskligt beteende vid olyckor.

Kontrollrummen vid Ij- och Piet Hein-tunneln i Nederländerna och Öresundstunneln har besökts och såväl det dagliga arbetet som funktionen vid olyckor har analyserats.

De statistiska analyserna av informationen visade att evakueringen kan delas in i tre skeden med statistiskt säkerställda fördelningar. Studien visade också hur evakueringstiden beror på enskilda faktorer såsom gruppbeteende, tiden tills bekräftande information ges via högtalarsystem, dörrbredden vid evakuering från tåg et cetera.

Beroende på hur arbetet i kontrollrummet är organiserat kan information till personerna som befinner sig i tunneln förväntas vid olika tidpunkter.

Rekommendationer om åtgärder som minskar evakueringstiden kan ges baserat på slutsatserna från försöken och jämförelser mellan dessa slutsatser och redan kända fakta som publicerats tidigare (se Kapitel 2). En slutsats från vägtunnelförsöken är att information via högtalarsystemet är vad som får merparten att besluta sig för att evakuera. Information på ett tidigt skede hjälper personer att besluta sig för vad de ska göra och bidrar till tidigare reaktion.

En annan slutsats från vägtunnelförsöken är att gruppbeteendet har stor betydelse för evakueringen. Detta är inte bara ett fascinerande fenomen utan något som kan användas vid planering för evakuering av tunnlar. Flaskhalsar uppkom vid nödutgångarna i tunnlarna vilket visar på ett behov av fler eller bättre utformade nödutgångar. Av försöken med evakuering från tågvagnar drogs slutsatsen att det vertikala avståndet mellan tågvagnen och avsatsen nedanför sannolikt påverkar evakueringshastigheten i stor utsträckning.

PREFACE

This report is originally written as a part of the UPTUN-project, a project aiming at cost-effective, sustainable and innovative upgrading methods for fire safety in existing tunnels. The UPTUN-project is being carried out with financial support of the European Commission under the Fifth Framework Programme, Competitive and Sustainable Growth Programme.

The report is the master's thesis of the Risk Management and Safety Engineering Programme of the Lund Institute of Technology.

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CONTENTS

1 INTRODUCTION

1.1 Background

Accidents in road or train tunnels are primarily a danger to the people directly involved in the accident. But if a fire breaks outs, these accidents become dangerous also to other people who happen to be around in the tunnel. The fires caused by accidents in the Tauern and Mont Blanc tunnels in 1999 are tragic examples of this (see Voetzel, A. 2002).

Means to prevent accidents are: technical improvements such as one-directional tunnel tubes and behavioural improvements such as alerting drivers earlier. This is a never-ending process aiming at safer tunnels, but not all accidents can be prevented. Therefore, measures are also required that mitigate the consequences of accidents. Technical measures are e.g. fire extinguishers in the tunnel and escape ways enabling people to leave the disaster tube and walk to safety.

However, the most successful way to achieve safer tunnels in the long run is to keep a risk management perspective including all factors that affect the safety of the tunnel users. This includes a struggle for improvements of the technical and behavioural means mentioned above but also a struggle to improve the role of the control room during accidents. These are all to be seen in a context as they influence each other.

1.2 Purpose

Focusing on tunnel safety from a risk management perspective the purpose of this report is to analyse the factors that affect the efficiency of crowd evacuations from road and train tunnels. These factors are analysed from two perspectives; first evacuation efficiency from the tunnel users' perspective is studied, then the role of the tunnel control room is analysed separately.

The purpose of the first part of the study is to quantify the time needed for tunnel evacuation. In the early moments of the accident, the fire will be small and the opportunity for escape is relatively good. Later, the fire may have grown and smoke may have filled the tunnel. It is important to know how much time is needed for evacuation, and to compare this to the time available for evacuation. In principle, the time for evacuation should be as short as possible.

The purpose of the study of the control room is to see how different ways to organise the work correspond to the tasks of the control room. As the actions taken in the control room directly affect the course of events inside the tunnel it is important to study how the staff should be organised to be as efficient as possible.

1.3 Theory and tests

The time needed for evacuation is not equal to the time needed to walk to the emergency exits. Accidents come by surprise and are unplanned, and the victims of a disaster should abandon their original plans completely. That takes time. Hence, adequate models of evacuation should have a stage called "awareness time" or "reaction time" before anyone starts to walk to the emergency exit (see e.g. Passenier & Van Delft, 1995). In the current report we use a third, optional, stage that stands between these two stages: *hesitation*. All three stages are based on observable behaviour.

The report presents the three-stage model. Based on observations in road and rail tunnels, the model finds its quantification. This quantification addresses both the transition between successive stages as well as the distribution of time required per stage. For road tunnels, a complete three-stage model of evacuation time is achieved. For rail tunnels, the output is a partial model because only observations on planned egress were available. In the report an example of how the model can be applied is provided and the possibilities for computer modelling are discussed.

The duration of the crowd evacuation is found to depend on the efficiency of the control room and when confirmative information about the accident can be provided to the people in danger in the tunnel. The efficiency of the control room is to a great extent a question of organisation.

The control rooms can be organised in two basically different ways; the organisation can be designed according to incident-specific or universal decision making.

1.4 Conclusions and recommendations

In this report conclusions are presented about factors of great importance for the evacuation efficiency. These conclusions are based on the results of several evacuation tests and thorough analyses. Also, recommendations are made about how to fasten the evacuation process.

The importance of information that confirms that the situation is dangerous given at an early stage is perhaps the most important factor. Information given at an early stage helps people make the decision to evacuate.

However, all single factors that are likely to affect the evacuation must be considered. It is the sum of all impressions compared to earlier experience that determines the action taken by any individual, and all these input variables must be put in a context. This is what risk management is all about – considering the effect of all input variables to plan for an optimal output.

2 LITERATURE REVIEW

As the overall focus of this report is quantification of the evacuation from underground spaces this is also the focus of the literature review.

A summary of the findings about what affects people's behaviour during an underground evacuation cannot be total. Neither is it fruitful to make a total scanning of everything covered of 70 years of studies in the field of psychology/human behaviour. Therefore the focus is set on what is most interesting to our study, i.e. road and train tunnel evacuation. The ambition is to make a representative selection of research findings from different sources.

The purpose of this chapter is not to discuss or to compare different reports from different researchers with the aim to come to any conclusions. The reason for summarising earlier published reports here is to make it possible for the reader to see what already is known, and to see how different topics are discussed. Further on in this report comparisons to articles described in this chapter will be made.

2.1 Human behaviour

The first topic we have studied is human behaviour during emergency situations from a general perspective. The concept of panic is discussed, as well as the human behaviour from an individual perspective. Several models that divide the human behaviour during emergencies into stages have been published during the last decades. A selection of these is presented below. Consistently the origin of the study is mentioned in the text and the complete source is given in the end of the report.

2.1.1 Panic

When it comes to crowd behaviour during emergencies much has been written about the tendencies for panic. In **Canter** (1990) much of the findings about human behaviour during fires are collected. During the first half of the 20th century researchers believed panic was common evacuation behaviour. Most of the later studies show that panic seems to be the exception rather than the rule in evacuations.

A prevalent viewpoint was that panic was the real source of problems; for example, in 1952 the Ministry of Works, UK, stated: "Panic is when an assembly audience results in a crowd jamming the exits and causing injuries quite apart from injury by fire. In the type of building now being considered, individuals as well as groups may become panic stricken. Lives may be lost, for example, through fear of using staircases in which there is some smoke but which would actually give safe passage out of a building".

However this definition has been questioned in various articles. E.g. **Sime** (1995, 1980) discusses the conception of panic. The clearest evidence of panic is said to be a sense of self-preservation at all costs, characterised by a-social or non-social behaviour in which family ties break down. Sime (1995) has shown that the crowd far from being a homogenous mass of individuals, who necessarily ignore each other, maintain close ties to group prior to and during flight to exits. In a situation of potential entrapment these ties evidently increase in strength.

Sime concludes that panic is mostly a rational reaction to the circumstances and that; hence, improving the circumstances avoids both panic and the problems associated with panic.

2.1.2 Individual perspective

Understanding the individual's behaviour during an emergency is of crucial importance for understanding of the evacuation in general. It is clear that the human mind goes through several stages from the moment that an accident occurs to the moment that the situation is safe or normal again. If an evacuation has to take place the individual has to make the decision to evacuate as early as possible. It is easy to understand that several factors affect the individual's behaviour. Several explanatory models, which are the results of extensive research, exist (see e.g. Wickens & Hollands, 1999).

In studies of the integration of psychology and engineering **Sime** (1995) presents four factors and their relationships to human behaviour during evacuation: (A) design and engineering * (B) communications technology * (C) crowd management * (D) crowd behaviour and movement. These factors should be considered in an early stage of the designing of an evacuation system.

Passenier & Van Delft (1995) divide the behaviour into four stages. Stage 1 is waiting for the congestion to clear up. Motorists don't consider the situation dangerous. Stage 2 is threat assessment; motorists become aware about the danger and start looking for refuge. Stage 3 is preparation for the flight. Personal property is secured, clothing adjusted, and goodbye is said to the car. Stage 4 is going to and through the escape exits, see figure 2.1 for details.

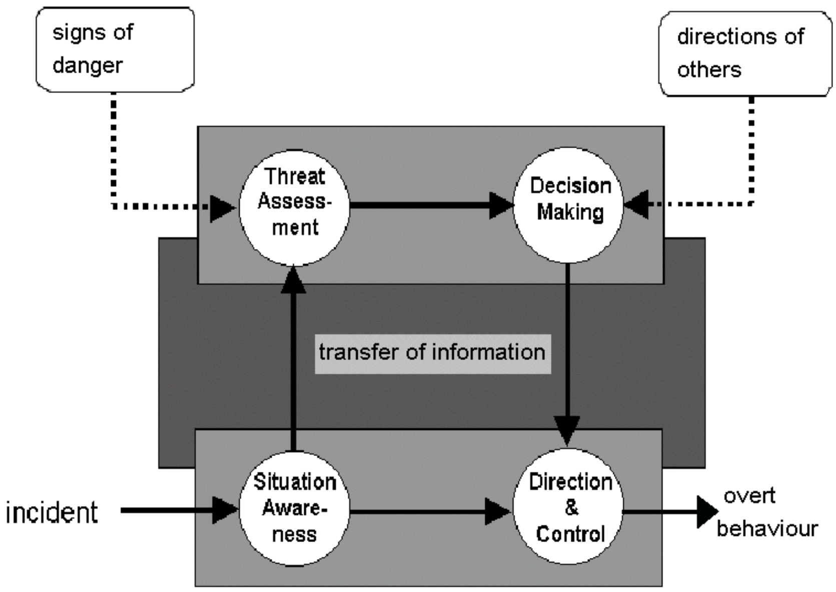

Figure 2.1 The four stages. Source: Passenier & Van Delft (1995)

The four stages can overlap. Motorists on their way to the emergency exits, Stage 4, may remember that they forgot to lock their car or to take their notebook, and return to do so, back to Stage 3. And some motorists can be in Stage 4 while others are still in Stage 1.

Canter (1985) suggests that the education, training and publicity of information should enable people to understand the problem and to make them able to cope effectively with fires. This suggests that they will respond properly to early indications of the presence of fire if they have a clear plan of action. For design, the broad consequence of studies is to show that traditional fire protection measures (hardware) are not enough. Design must also allow for what people will actually do in fires. This can be compared to the factors A and B presented by Sime (1995) and discussed above.

Canter (1985) divides the human behaviour during and before emergency situations into five stages. These five stages are:

1. Pre-fire activity
   If a person is engaged in a well-known activity, e.g. eating a meal in a restaurant, the implications for subsequent behaviour are considerable. The pre-fire activity will influence the type of cue received and the readiness with which one reacts.

2. Cue reception
   Initial cues are usually ambiguous. Investigation takes place to resolve ambiguity. This helps establish the nature of the situation and provide more detailed information on how to act. Information may come from others but has been found to be frequently inadequate for effective behaviour. This is to be compared to the conclusion of the Tyne and Wear Metro-studies supported by Proulx and Sime (1991) that early and adequate information provides proper evacuation behaviour.

3. Interpretation: Definition of the situation
   Because people act according to their definition of a situation the clues and information that lead to this must be taken into account, with due consideration of the influence of both the place and roles of the people concerned. In the model it is pointed out that if people present are not informed appropriately, ineffective behaviour on the part of the public will ensue.

4. Preparation
   Before acting preparation takes place with three different possibilities of behaviour. These are instruction, exploring or withdrawing.

5. Action
   The action depends considerably upon role, activity, earlier behaviour and experience. Early definitions of the situation make early evacuations or effective fire fighting possible to occur.

Bickman (1977) describes a conceptual model that illustrates factors thought to influence human behaviour in a fire emergency. The model involves three basic stages:

1. Detection of cues
2. Definition of situation
3. Coping behaviour

The behaviour during each stage is affected of six categories of variables, namely:

a. Physiological/physical
b. Interpersonal
c. Education and preparation
d. Social
e. Fire characteristics
f. Psychical environment.

Bickman gives a fundamental picture of the factors on which the human behaviour in emergencies depends.

Canter (1990) divides the evacuation into four stages, each representing a phase in the individual's behaviour during the emergency. The first stage is cue reception. This is followed by a phase where the individual seeks for additional information. Thereafter the individual decides to evacuate, which is Stage 3. Finally the individual chooses exit routes, stage four.

Canter discusses the role of appropriate information in the different stages. In Stage 1, appropriate information results in faster understanding of the situation. In Stage 2, appropriate information reduces the time taken to decide on actions. The effect of information during Stage 3 is a reduction in time to decide to evacuate. And finally in Stage 4, information reduces the time to leave the building.

Proulx (1993) has created a model for stress behaviour during fire emergencies. The model is based on three characteristics, pointed out by **Idzikowski and Baddely** (1993).

The first factor is the person's predisposition to stress. The model states that everyone has a trait-anxiety that does not vary much during a person's lifetime and a state-anxiety that depends on the situation. Both can influence performance. The second factor is the subjective assessment of danger. What one person considers dangerous another may not, which influences the stress level. The third factor is previous experience from similar events. Earlier experience will have an influence on the person's reaction on a new situation, either positive or negative.

Proulx has built her stress model from the variables information processing, decision-making, problem solving and stress. Information processing is a prerequisite to decision-making, which allows problem solving. The model consists of loops, where the first loop deals with the ambiguous information of early cues. Depending on how a person evaluates the information and the three factors discussed above, other loops follow with more and more uncertainty. The decision-making becomes harder the more uncertainty that is involved in the actual loop. On the other hand early and precise information makes the decision-making faster and does not give room for uncertainty and confusion.

There are several different models developed by Bickman, Canter, Sime and Proulx; in many cases these are the result of decades of research. Either the models are based on different stages that the human mind undergoes during an emergency or they are based on factors that affect the human behaviour. The conclusions of these models are similar, both with regard to stages that the human mind goes through, and with regard to factors affecting behaviour. For example all stage-models begin with lack of information, (cue reception etc.). Later comes a decision-making stage and finally an evacuation stage. Also similar factors affecting the human behaviour are considered in different models, for example earlier experiences and group behaviour.

2.2 Information

It is unquestionable that most people facing an accident have a lack of information. Is there a danger? If yes, how dangerous are the risks? Am I supposed to help victims or to run to safety as soon as possible? If the accident takes place in a confined space, where are the exits? It is clear that lack of information or incorrect information affects the human behaviour. The information provided should be designed to make it easy to make correct, fast decisions in a stressful moment.

2.2.1 The need for information

Canter (1985) suggests that behaviour during an emergency is characterised by the search for confirmatory information. At the same time the early stages of a fire are characterised by ambiguous information. Alarms that give information rather than just loud signals have great potential for reducing delay in response. Appropriate information in early stages helps understanding what is going on and dealing with the rapid changes in the situations.

Canter et al (1992) emphasise the need to provide people with the information necessary to be able to correctly interpret what is happening around them. Canter states that this is because people actively interpret their surroundings when dealing with the world rather than react passively. People see what is going on around them and try to interpret or make sense of it.

Keating (1985) discusses psychological factors critical in directing behaviour during fire emergencies. He comes to five conclusions:

1. Under heightened anxiety a person's focus becomes very narrow – only allowing processing of the most obvious elements of the environment. Keating's practical implication is that all communications should be simple, brief, and obvious. Complicated and numerous written directions will not be effective. Special consideration must be given to the proper positioning of these signals, including architectural techniques.

2. During ambiguous situations people will mime the behaviour of the significant others. It is important that those who are responsible for the fire evacuation have a proper education and a proper authority, because people will tend to look at them and do whatever they say.

3. In critical situations when there is no time to analyse the situation people fall back to familiar behaviour. To make people aware of alternative moods of egress there is a need to break the instinctual type of reaction.

4. An individual's cognitive processing ability is limited in emergencies, consequently repetition and brief representations about proper procedures are essential. This is a natural consequence of the heightened anxiety.

5. Slightly elevated levels of carbon monoxide can distort people's ability to make proper judgements.

Proulx & Sime (1991) have analysed an evacuation simulation that took place in Tyne and Wear Passenger transport executive in Newcastle, UK. Five different ways of alerting people were evaluated in the simulation. These where:

1. The alarm bells sounded, no further assistance took place in the evacuation

2. Two staff members present on the platform. These knew that there was to be a fire drill but not how it was planned. When they heard the fire bell, they contacted the control room and were instructed to check the location of the smoke detector that had activated, to give a public announcement (PA) to “evacuate the station” through the local PA system, and to direct the evacuation of all passengers.

3. No staff members present on the platform. Each 30 s the control room issued a PA “Please evacuate the station immediately. Please evacuate the station immediately. “

4. The control room issued directive PA:s telling passengers on platforms to board trains and the others to leave by the exits. Two staff members assisted the evacuation in accordance with the PA:s from the Control Room.

5. The control room in full operation issuing directive PA:s. No staff members present on the station. The PA:s in evacuation 5 were different from the ones in evacuation 4 because information was given about the incident, its location and what was expected from people in the station.

The conclusions from the tests are that more information results in better evacuations. Without relevant information people have no way to judge and take decisions in relation to a specific situation and they easily behave in a way that afterwards seems inappropriate.

The information used to interpret the situation can come from different sources. **Proulx** (1993) discerns three general ways:

1. Information provided by the emergency itself; people see smoke or flames e.g.
2. The building provides information through alarm or messages via the PA system
3. Other people, staff members or users, provide information by what they do or say.

2.2.2 Information design

The existing surveillance system including PA-system and closed circuit TV can often be used to guide people who are evacuating. In this case the people in the control room guide the evacuating people to the nearest and best exits. The staff members in the control room need good communication skills to manage this.

To support appropriate evacuation behaviour **Canter et al** (1992) point out the importance that people are not only informed as soon as possible of the need to take specific action but also, that this information provides sufficient details for people to help them behave in the right way. In this:

1. Information should be given rapidly
2. Information should be informative
3. Early action should be emphasised

This can be compared to the three information characteristics that according to **Proulx** (1993) have an impact on interpretation of the situation. That is:

1. Information quality
2. Information quantity
3. Information relevance

The purpose of the information is, as Canter et al (1992) state, to provide an early response and a proper behaviour of the people in an emergency.

Proulx & Sime (1991) come to the conclusion that it is important to ensure that the public can perceive and understand the information provided by the communication system when it is in daily use. It is essential to build up a climate of confidence through legible architecture, reliable information and building management tailored to the users.

Another factor affecting the information receiving is the experienced reliability of the source. **Canter et al** (1992) discuss the difference between uniformed staff such as ticket collectors and police officers or fire fighters. Because of the ordinary role of for example a police officer people trust the information given by him more than they trust information given by a ticket collector.

In the study of the Tyne and Wear Metro evacuation **Sime** (1995) shows that very different evacuation times and patterns of behaviour can be achieved in the same psychical settings by altering the information available to people about a potential danger. In this case evacuation times were reduced by at least ½ or even 2/3 (in this case from approximately 15 minutes to 7 or perhaps 5 minutes) by reducing the time for people to start to move.

2.3 Empirical knowledge

Analyses of accidents can give pieces of information that are impossible to achieve through experiments and simulations. Empirical information can also tell whether conclusions from experiments are likely to be true or not. The accidents in the Mont Blanc and the Tauern tunnels in 1999 and the fire in the King's Cross station 1997 are examples of tragic incidents that have provided invaluable information.

Voeltzel (2002) provided a lot of information about actual behaviour during the fires in the Mont Blanc and Tauern tunnels in 1999. The main conclusions are that people will stay in their cars as long as they do not experience the threat of the fire.

Canter (1990) tested how people predict fire growth rates and patterns. The result was that people are not very good at predicting the actual growth rates (fires grow exponentially over time). When the fire is small people do not feel threatened because they do not realise how fast the fire will develop. No action to start evacuating is taken and when people finally are threatened from the fire it can bee too late because of the smoke and the heat.

In the Mont Blanc tunnel fire many victims were found inside or near their vehicles. This means that they did not start evacuating in time. In the Tauern tunnel fire, most of the people had the sense to flee on foot. Only three people stayed in their cars and died. Not to forget, a lot of people got out at an early stage, which saved their lives.

From analyses of the Kings Cross fire in November 1997 **Canter & Donald** (1990) came to the conclusion that human behaviour depends on the role of a person. For example a commuter who travels every day with the same goal is likely to follow the same pattern as usually even during an emergency. Travellers with a certain goal do not listen to the information provided from railway staff members and they act just like they would do if there was a common delay and not a fire. Also, the police in the metro station act according to the policemen's role and try to solve the problem. The policemen have a greater possibility to change the behaviour of the passengers because of the natural authority of a policeman. The railway employees do not have the same authority and therefore they do not have the same possibility to change the passengers' behaviour.

3 ROAD TUNNEL TESTS

The purpose of Chapter 3 is to determine the time spent in different phases from the moment that an accident occurs in a road tunnel until the moment that all people in the tunnel are brought to safety.

The first challenge is to provide a model of the behaviour during the time spent in the tunnel. This model should consist of different phases that describe the course of events starting from the moment when the accident occurs. It must be possible to analyse the phases in a scientific way and to quantify each phase. But most important, the model should be as close to the reality as possible.

We start with a model of Passenier and Van Delft (1995). In this model, perception of the incident makes motorists aware of the situation. They judge the situation with regard to threat. In case of a serious threat, they will consider plans for defensive action and, finally, decide to adopt a specific plan, see figure 3.1. Execution of the plan requires direction and control. Passenier and Van Delft developed their model for naval command and control. The incident is, for example, an approaching radar or sonar contact; the decision is to change course or to deploy certain weapons. We apply the model to the evacuation of motorists from a tunnel. This model is chosen as a representative model from several quite similar models of human behaviour.

We assume an accident followed by a traffic jam. Traffic jams are not necessarily caused by an accident, and most traffic jams do not imply the need for evacuation. Therefore, the situation awareness is "an ordinary traffic jam"; the threat assessment is "I could be too late at my destination"; the decision making is "what can I do?" and no action is taken (the module Direction & Control is idling). To see more, motorists may step out of their car. An additional motivation is stretching the legs.

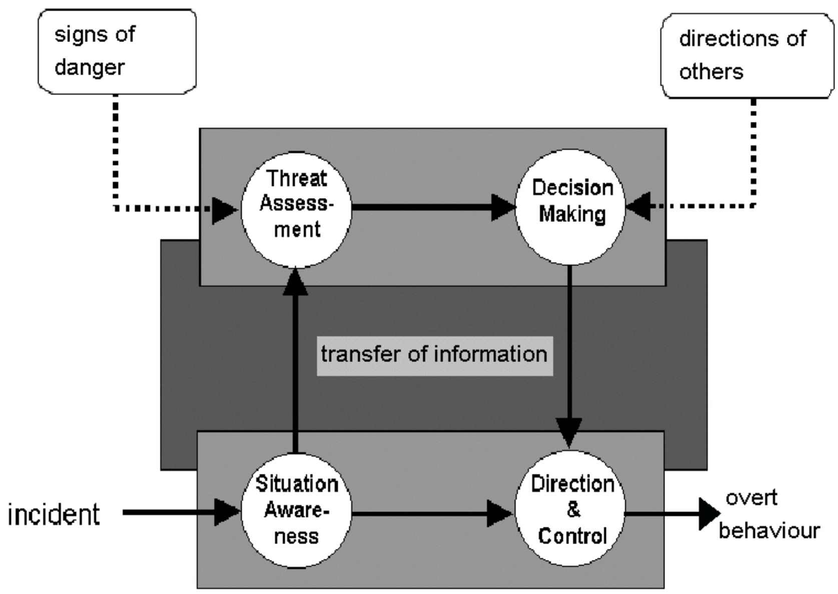

Figure 3.1 The four stages. Source: Passenier & Van Delft (1995)

Seeing the vehicle burning adds fresh information. Motorists become aware of the reason for the traffic jam. The threat of arriving too late increases but, again, there is nothing motorists can do. Some, however, may begin to revise the threat, including the threat coming from smoke and heat. Possible action plans are (a) guarding the interior atmosphere of the car (behaviours like closing the windows and shutting off the ventilation), (b) considering getting away from the accident by car and (c) considering fleeing afoot. Leaving by car requires driving backwards, a behaviour that is dangerous and forbidden. Not many motorists will adopt this action plan, and if they do, the probability of success is small. In the tunnel fire in Ekeberg in Norway the traffic behind the fire became all knots and tangles because motorists tried to back away by car (Skarra, N. 1997). This action is no solution except in an almost deserted tunnel.

Motorists will not act immediately. They will hope and expect that "something" will happen and restore normalcy. If information, however, continues to arrive raising the threat assessment, decisions to act will be made and executed. Such information can be escalation of the fire, others fleeing the fire, or instructions of the tunnel operator. The urgency to act increases and the probability of motorists actually leaving their cars for the emergency exits increases.

Based on this model we can try to define a Stage 1 with drivers sitting passively in their cars and waiting for the congestion to clear. The signs of danger are "moderate" and especially drivers far away from the accident are unlikely to assess any threat. A few motorists may step out of their cars to stretch legs or to look for more information (orientation behaviour).

Stage 2 can be defined as the first assessment of threat. Those who react will look for more information (orientation behaviour) and proceed to the next stage if the threat is confirmed.

Stage 3, decision making, follows if a certain level of threat is exceeded. The danger is clear, but what action should be taken? Motorists consider fleeing from their cars. They will step out and look for where to go. They will also (briefly) consider how to abandon their car – doors locked, lights off? A few may consider the car as the safest place, remain there, and perhaps close the window and shut off the ventilation. Others may try to fight the fire using extinguishing equipment. Seeing others flee is a strong signal of threat, and imitation is likely, the group effect.

Once the decision is made, drivers will be on foot and go for safety. Where that safety can be found they may see directly (provided that the escape ways are adequately indicated). Where others go is taken as an important suggestion of safety (although others may be mistaken). What the tunnel operator instructs them to do is a very strong suggestion that is likely to be followed. Assuming that the escape route is adequately marked, people will walk (or run) to safety. Many will keep looking back and walk slow, curious about the disaster and concerned about their car. Some will go back to their car to lock it or to get something that was forgotten when they left it the first time. This would be Stage 4 in a four-stage model.

The four stages seem plausible enough. In a sense, each motorist will go through these stages individually. For an observer of video tapes it is, however, impossible to distinguish when one stage ends and the next stage begins. It is hard to differentiate between stepping out of the car because the motorist realises that there is some danger and stepping out of the car just to stretch legs.

For observational analysis, a more pragmatic definition that enables a clear differentiation among different stages is required. This also requires observable behaviour. We use the following behaviours: stepping out of the car, remaining near the car or leaving it, and going towards one of the emergency exits. If there is a period of time between leaving the car and going towards the exit, we call that "hesitation"; the decision to evacuate has yet to be executed.

This defines three clearly discernible stages: 1 – the time in the car (from the accident until the doors are opened), 2 – hesitation (the time between opening the door and the moment the driver begins walking away from the car towards an exit) and 3 – the actual walk towards the exit – see Figure 3.2.

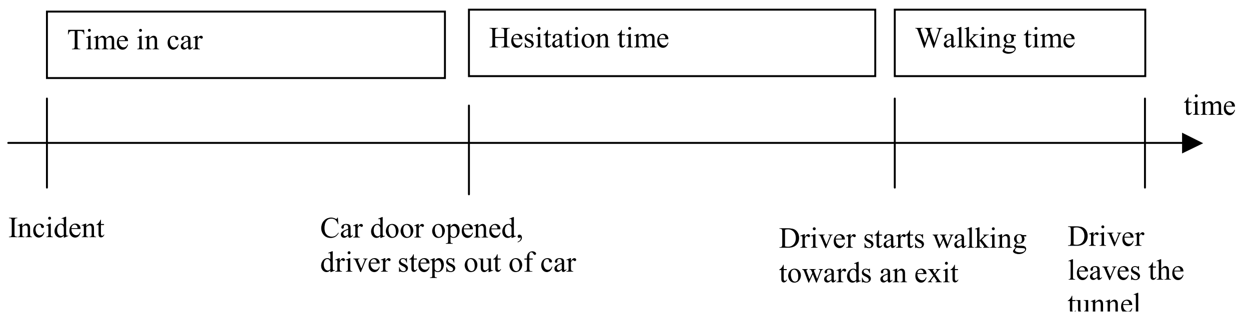

Figure 3.2 The three stages in the model.

With this model we will test how the announcements of the tunnel operator affect the behaviour and study the effects of group behaviour. The three stages are easy to quantify and they should be close to the reality. They correspond to the four stages in the first model but the starting point is how a spectator sees the course of events. Situation awareness, threat assessment and decision making all takes place during the time in the car and during the hesitation time. It is however not possible to determine when any of these three stages start or end.

What are possible to determine and to analyse are the three stages in the time axis above. It is possible to see how for example announcements via the loudspeakers or the group behaviour affect the duration of the stages and to study relations and distributions.

The overall purpose of quantifying the information is to make it possible to handle the information in a statistic correct way. This chapter should result in theoretical distributions that correspond to the empirical distributions achieved from the quantified data. Theoretical distributions expressed in statistic terms with mean values and standard deviations make it possible to combine the different stages and make conclusions about the total evacuation process. This is described further in Chapter 6.

3.1 Method

To collect information about the behaviour of road users who come to a standstill behind a burning vehicle in a tunnel tests were carried out in January 2002. In total nine tests were carried out in the Benelux tunnel in Rotterdam in the Netherlands.

In the tests a Heavy Goods Vehicle (HGV) followed by cars in both driving lanes entered a one-way tunnel with two driving lanes. In the middle of the tunnel, smoke started to develop from the truck that slowed down and stopped, blocking both driving lanes. See figure 3.3 for the test settings.

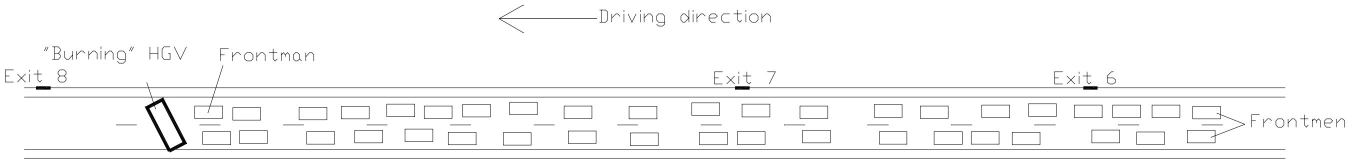

Figure 3.3 Test settings in the nine tests.

Approximately five minutes after the truck stopped an announcement was made via the loudspeakers in the tunnel, saying "Attention, attention, there is an explosion hazard; I repeat, there is an explosion hazard". After two more minutes the drivers were told to evacuate the tunnel.

In the first seven tests the participants had been informed in advance that the purpose of the test was to study driving behaviour. Although this specific time they were told that they were only driving through the tunnel to get familiar with it and the study itself would take place later. Therefore they did not expect that an evacuation could take place. The last two tests were control tests (Test 8 and 9); in these the participants were told before the test that they should evacuate as soon as the HGV comes to a halt.

The participants were told to come by car alone, i.e. only one person in every car. There were some minor violations to this instruction; in six cars two individuals appeared. In these situations only the driver's behaviour has been analysed. However, these minor violations of the instructions are not believed to have affected the results.

In each test four cameras recorded in the tunnel. The camera view is from the HGV and 140 meters back. Forty to fifty cars participated in every test, but the queues were longer than expected and only 25-35 cars were in view of the cameras each time. The recordings permitted behavioural analysis of a total of 193 drivers. Figure 3.4 shows the four camera angles and figure 3.5 shows the HGV with two lanes of stopped cars behind it.

Figure 3.4 The four camera angles in the tests.

Figure 3.5 Stopped cars behind the burning HGV

In Appendix A a more detailed description of the test settings is found.

3.1.1 Analyses of the tests

The basis of the analyses was observation of the videotapes completed with indications of the moment of loudspeaker announcements (2 announcements for each experimental test). The scheme of Figure 3.2 was followed. Moments recorded were (a) the moment the HGV came to a full stop, (b) the moment the individual driver put his feet on the ground, (c) the moment the individual driver started walking towards the emergency exit, and (d) the moment the individual driver finally passed through the emergency exit.

The motorists walked either uphill or downhill when they had left their cars. The difference in walking speed depending on the slope was also analysed.

More detailed descriptions about how the tests were carried out as well as the plan for the analysis are presented in Appendix A.

3.2 Results

Because the drivers in Test 8 and 9 were informed about the purpose of the study conclusions based on all nine tests can only be made for the last stage in the behavioural model. When it comes to Stage 1 and 2 the results can only be based on Test 1-7. The method and the chi-square tests are described in Appendix A.

3.2.1 Group behaviour

The time from the moment that the HGV stops until each person reacts and opens the car door is displayed in the figure 3.6 as cumulative frequencies. Every test is represented by one curve. Most curves have similar steepness but what separates the curves from one another is the starting point for most of the participant's actions.

T = 0 in the figure is the moment when the announcement in every test is made.

The graph indicates clear group behaviour within the test groups. As soon as any action was taken by one person within the group, more people followed and started to react. Evidently people sat tight in their cars and prepared to react, but were unwilling to act until anybody else acted.

In most tests the major part of the test group reacted after the announcement and a minor part reacted at an earlier stage. There seems to be group behaviour that is referable to minor populations than the test groups; in Tests 4 and 2 a considerable part of the population formed a group that reacted before the announcement while in the other test groups only minor parts reacted before the announcement.

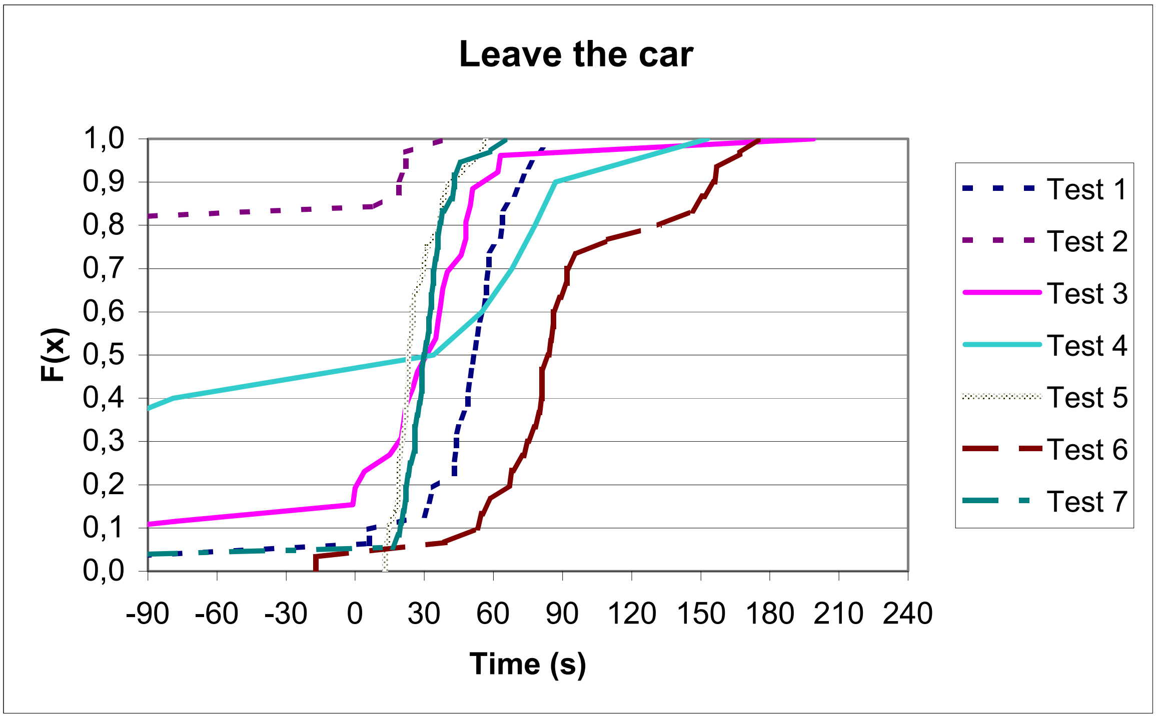

Figure 3.6 Cumulative frequencies of people leaving the car (the announcement "explosion danger" comes at T_O; the number of participants varies from 10 in test 4 to 36 in test 7).

Figure 3.7 Motorists leaving their cars. Almost all motorists leave their cars at the same time.

When it comes to leaving the tunnel the group behaviour is even clearer. In four of the tests almost all the people left the tunnel within 60 seconds, see figure 3.8.

Figure 3.8 Cumulative frequencies of leaving the tunnel by emergency exits over time (the announcement "explosion danger" comes at T_O; the number of participants varies from 10 in test 4 to 36 in test 7).

3.2.2 Leaving the car

The population is divided into two parts. The first part is those who left their car before the announcement and the second part consists of those who left their car after the announcement was made.

Since the announcement took place at slightly different times in the different tests a mean value is used to estimate the time. The mean value of the announcement was 331 seconds after the HGV stopped.

In the studies of the first population, people reacting before the announcement, time = 0 is when the HGV stopped. In the study of the second population, where the motorists react after the announcement, time = 0 is when the announcement took place 331 s after the HGV stopped.

Before announcement

In the seven tests 38 motorists left their car before the announcement. 3 motorists, who reacted before the announcement was made but after 331 seconds are not considered since they reacted at a time that does not exist in all the other tests. This is because the announcement was made only approximately at 300 s, when some people reacted at T = 340 s the announcement has not yet been made in these tests. Those 3 motorists are not calculated because the times that they react do not exist in the model. Since 3 drivers are excluded, 35 participants are in the analyses.

Also the “Before announcement”-population is divided into two groups, before 100 seconds and after 100 seconds after the HGV stopped. This is made because the distribution reveals two more populations; the graph has two tops. The first group consists of 18 persons and the second consists of 17 persons. Both the populations are normal distributed. In the figure 3.9 below, which shows all motorists who reacted before the announcement, a significant change in the distribution between 80 and 130 seconds is evident.

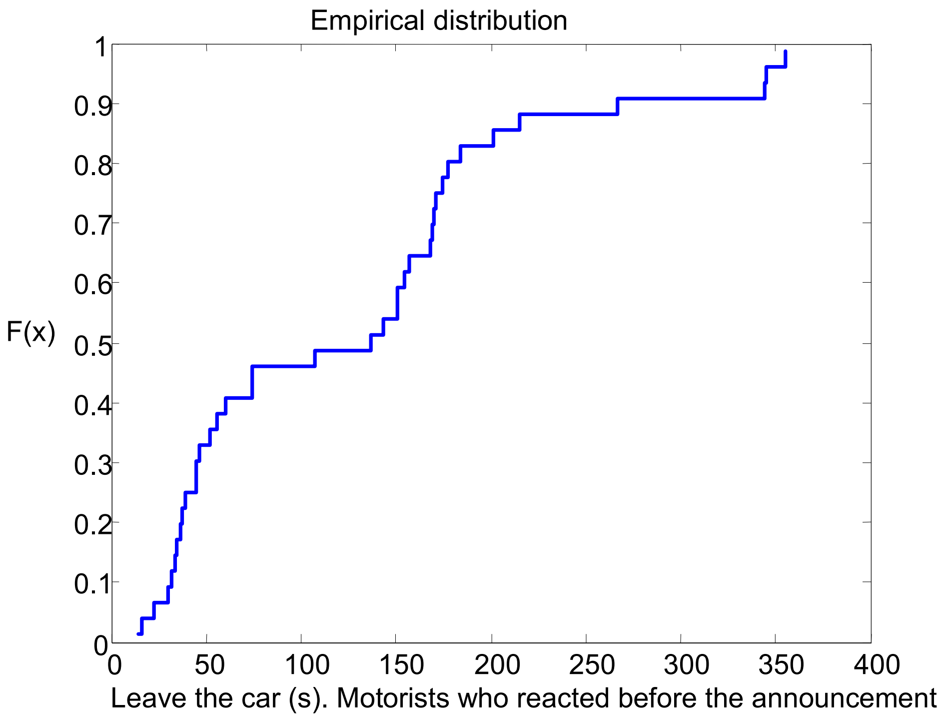

Figure 3.9 All motorists who reacted before the announcement. This is a significant 2-population distribution. The first is until 80 seconds and the second is until 300 seconds. Those three after 300 seconds has been excluded.

The statistical characteristics for motorists who acted before the announcement is:

X = (0.51) Norm (41.6; 17.1) + (1-0.51) Gumb (28.8; 155)

In the following two graphs the “Before announcement”-population is divided into two and shown in one graph each. The Normal distribution is represented by the red curves.

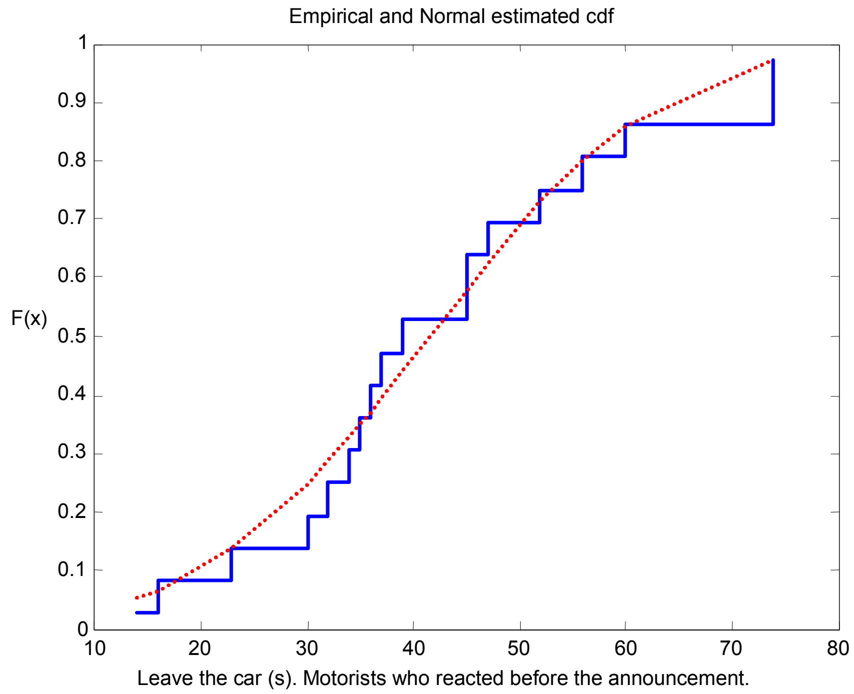

Figure 3.10 The data from the tests and the estimated normal distribution. This is the first population until 80 seconds. The estimated distribution is Norm (41.6; 17.1).

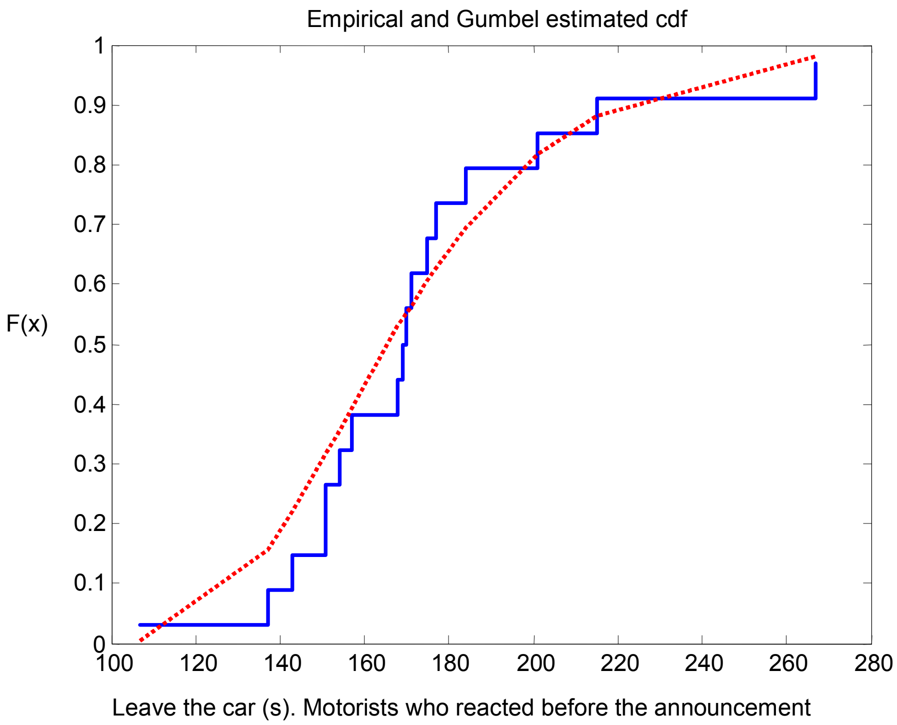

Figure 3.11 The data from the tests and the estimated gumbel distribution. This is the second population up to 300 seconds. The estimated distribution is Gumb (28.8; 155)

After announcement

Most of the people, 155 persons, reacted after the announcement was made. These are collected in one distribution. 155 divided by 190, the total number of persons in the tests excluding 3 persons that are disregarded, is 0.816. That means that 81.6 % reacted after the announcement. The best-fitted distribution for those is a Generalised Extreme Value (GEV) distribution and is shown in the figure below.

The statistical characteristics are:

X = GEV (-0.22; 19.91; 33.08)

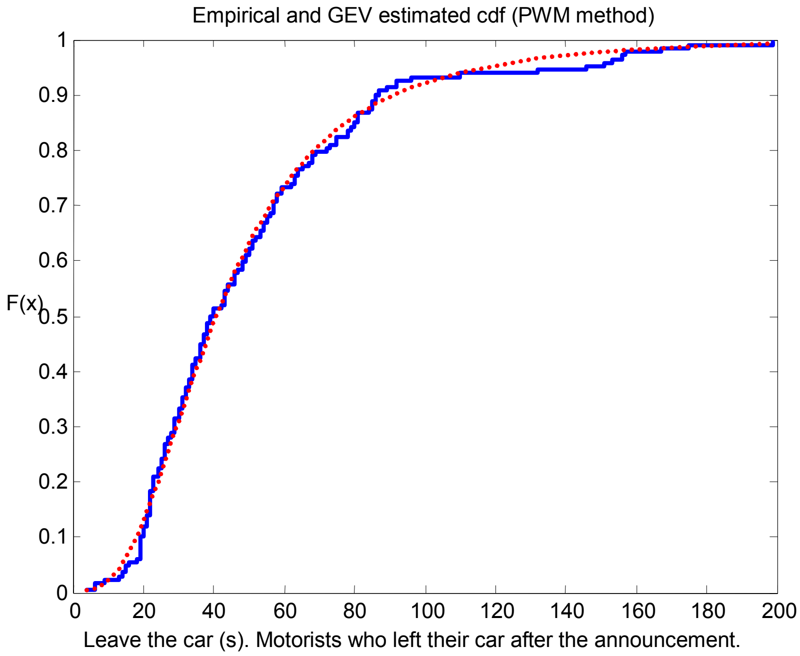

Figure 3.12 The data from the tests and the estimated Generalised Extreme Value (GEV) distribution. This is the third population and t_0 is 331 s after the HGV has stopped. The estimated distribution is GEV (-0.22; 19.91; 33.08).

Total population

The total distribution is based on 193 observations on seven separate tests. 3 of the observations are negligible because they are not in the right timescale.

The first and the second group each comprise 9% of the population. The time lost in the car (X) is normal distributed:

X = Norm (41.6; 17.1)

and

X = Gumb (28.8; 155)

for the two groups, respectively. The times are seconds after occurrence of the incident.

The third group comprises the majority of the population, 82%. These reacted to the announcement. The time lost in the car is described as a generalised extreme-value distribution:

X = GEV (-0.22; 19.91; 33.08),

with times (s) after the moment of announcement.

Combined estimates of the total process of leaving the car can be given only if the moment of announcement is known. For the current tests, where the announcement came 331 s into the incident, the total process of leaving the car can be represented by:

X = (331+(0.816 (GEV (-0.22; 19.91; 33.08))))+((1-0.816) 0.51 (Norm (41.6; 17.1))+(1-0.51) (Gumb (28.8; 155)))

The total distribution is described in the figure below.

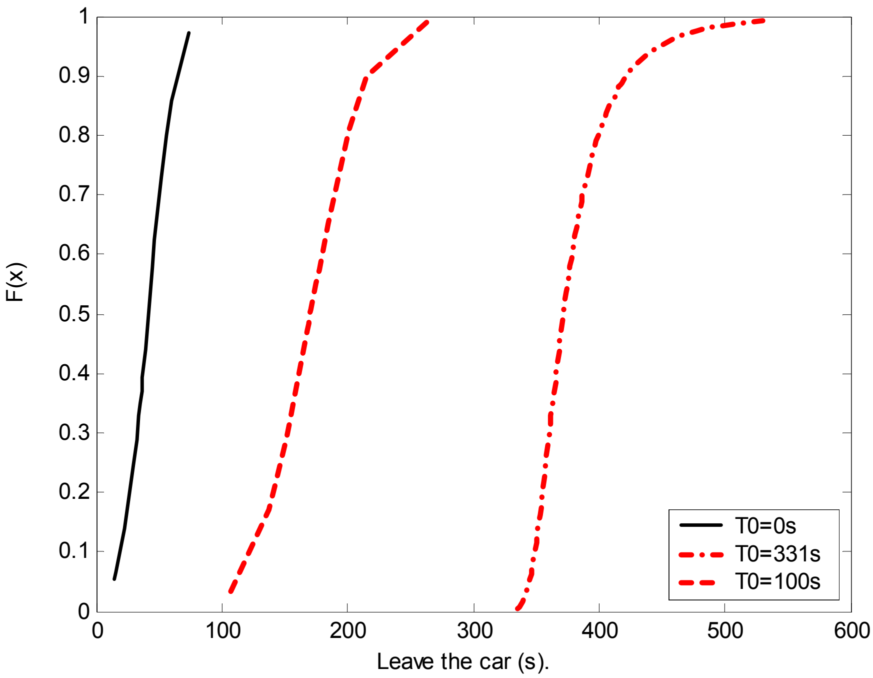

Figure 3.13 All three distributions in the same timescale.

3.2.3 Hesitation time

When analysing the duration of stage 2, the hesitation time, the group again is divided into two populations, one population with people who left their cars before the announcement and one with people who left their cars after the announcement.

Inspection of the hesitation duration reveals that those who reacted before the announcement hesitated much longer than those who reacted after the announcement. In the *before* group (n=35), hesitations longer than 100 s are observed 26 times, whereas the *after* group (n=155) has only one hesitation > 100 s. We describe the hesitation duration of these groups separately.

Also, participants who did not hesitate at all are treated separately. In total 46 motorists did not hesitate. Three of them left their cars before the announcement.

Before announcement

Of the 18 % who reacted before the announcement we conclude that 8 % did not hesitate at all, (3/35).

The hesitation duration of the before group can be described as:

Hes(before) = 0.08 (hes = 0) + (1-0.08) Norm (151; 81)

The empirical and estimated distributions, the dotted line, are shown in the figure below.

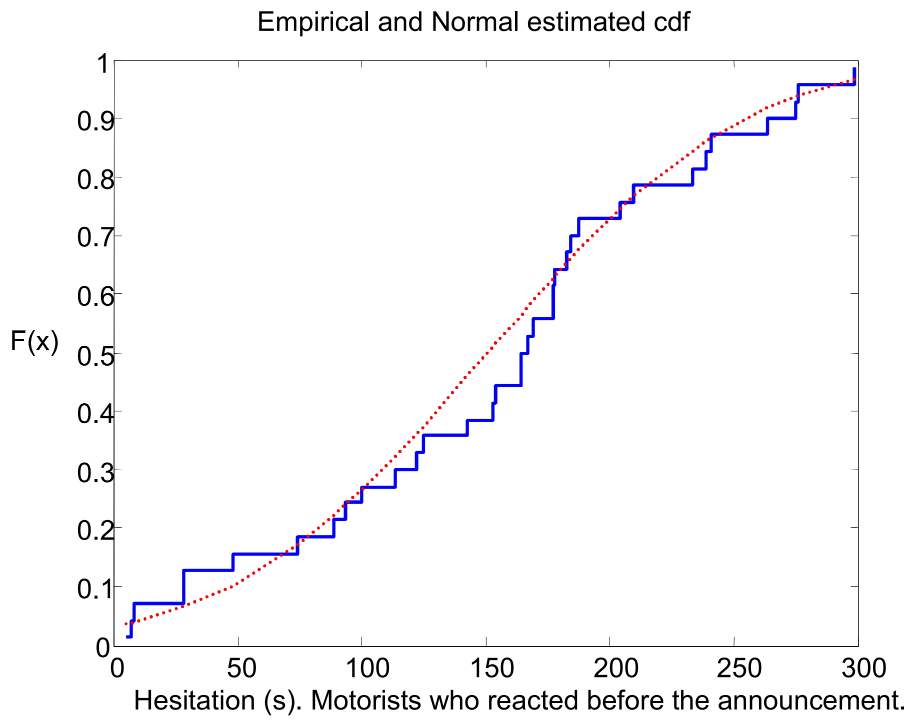

Figure 3.14 Approximated and actual distributions of hesitation duration for those who reacted before the announcement. The estimated distribution is Norm (151; 81)

After announcement

Of the 82 % who reacted after the announcement we conclude that 28 % did not hesitate at all (43/155).

The hesitation duration of the *after* announcement group can be described as:

Hes(*after*) = 0.28 * (hes = 0) + (1-0.28) * GEV (-0.44; 6.13; 8.42)

The distribution of those who hesitated is estimated by the dotted line in figure 3.15.

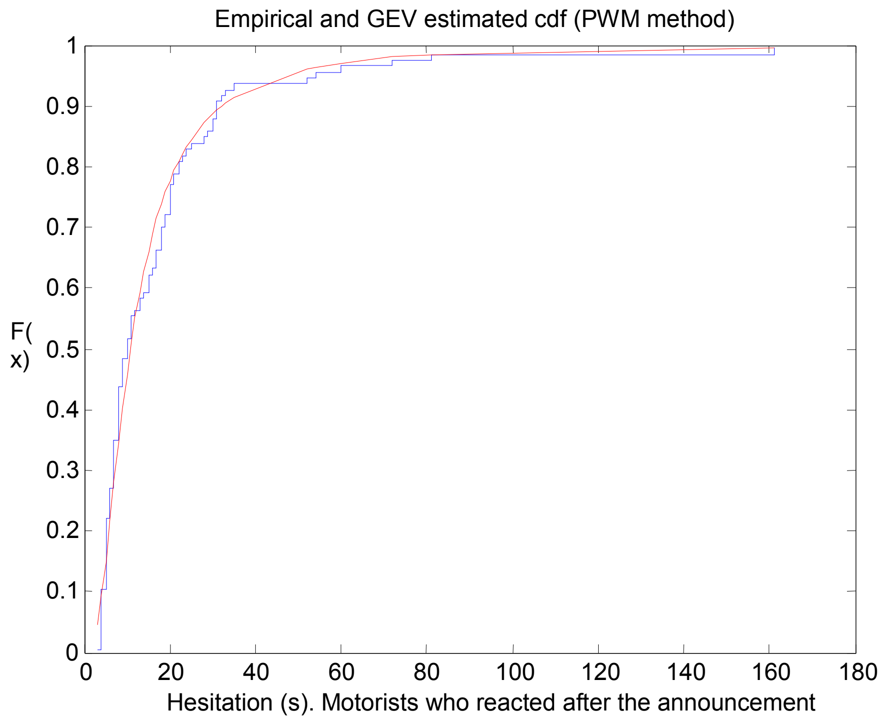

Figure 3.15 Approximated and actual distributions of hesitation duration for those who reacted after the announcement. The approximation is GEV (-0.54; 6.10; 8.31).

3.2.4 Walking speed

The walking speed is achieved by dividing distance by walking time. Perpendicular lines between the car and the emergency exit estimate the distance. The mean speed in the different tests is shown in the table below.

Table 3.1 The mean walking speeds and the standard deviation in all tests

Test	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Mean (m/s)	1,56	1,38	1,06	1,38	1,34	1,39	1,44	1,24	1,10
Std dev	0,60	0,53	0,38	0,74	0,52	0,53	0,52	0,58	0,46

The mean walking speed in Tests 1-7 is 1.37 m/s with the standard deviation 0.55.

If Tests 8 and 9 are included the mean walking speed becomes 1.33 m/s with the standard deviation 0.55 m/s. In Test 9 the area outside the emergency exit became crowded and therefore many participants slowed down before they reached the door area. In Test 8 the participants did not understand the instructions, “leave the car and evacuate”, thus the results from these tests are not reliable.

Therefore, the mean walking speed is based on the data from Tests 1-7.

The best-fitted distribution for walking speed is a Gumbel distribution and is shown in the figure below.

Walking speed = Gumb (0.4431; 1.1185) m/s

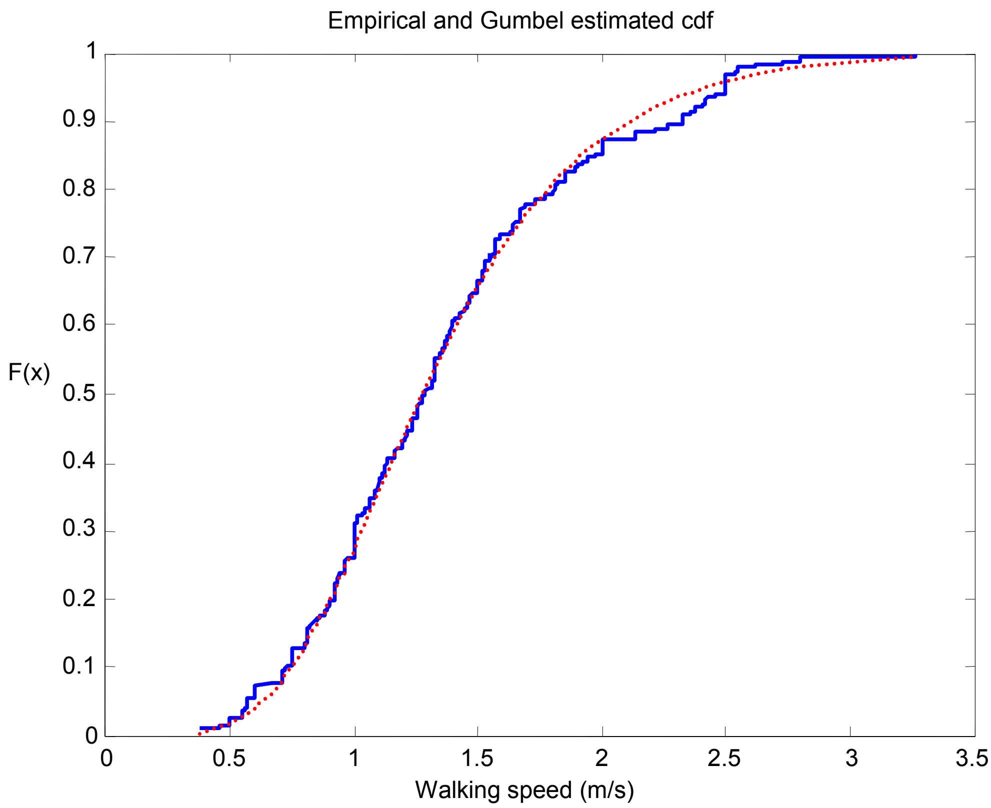

Figure 3.16 Walking speed in the Tests 1-7 and the estimated Gumbel distribution. The estimated distribution is Gumb (0.4431; 1.1185).

The Gumbel distribution fits well for 85% of the population. The curve representing the fastest 15% of the group is first a little overestimated and then underestimated. In total the estimated distribution reflects the data from the tests very well.

3.2.5 Closest emergency exit

No participants chose the exit beyond the HGV (Exit 8). Only in the last two tests (evacuation announced and HGV not burning), three participants of 71 went past the HGV. The conclusion is that motorists will not pass a burning obstacle.

The motorists further away from the HGV could choose either Exit 7 or Exit 6. Almost always they chose the nearest exit. In all nine tests, both unannounced and announced, 102 cars were observed between Exits 6 and 7, but only 6 motorists chose an exit that was not the closest one. These drivers all walked in the driving direction. In short, 94% selected the nearest exit; the few selecting another exit always went forward.

3.2.6 Difference between downhill and uphill

There is a difference in altitude in the Benelux tunnel with the tunnel's lowest point situated between Doors 6 and 7. Therefore the motorists who evacuated from a position between these doors had to go uphill. The distance between exit 6 and 7 is 50 m. Motorists who stopped between the HGV and door 7, walked downhill when they evacuated. The distance between the HGV and exit 7 is 100 m. An analysis was made to see whether there is any difference in walking speed between people walking downhill and uphill. Figure 3.17 shows the layout of the tunnel. The gradient of the slope is 4.5% in the tunnel.

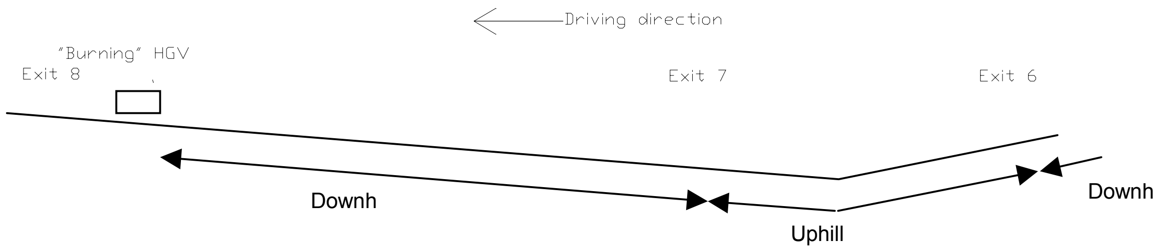

Figure 3.17 Layout of the tunnel. The tunnel's lowest part is between Doors 6 and 7.

Table 3.2 below shows the drivers walking uphill and downhill in every test. In Test 1 for example, Drivers 1-8 in the left lane stopped between Door 7 and the HGV and Driver 16 in the left lane stopped between Doors 5 and 6. These drivers walked downhill. Drivers 9-15 in the right lane stopped between Doors 6 and 7 and walked uphill et cetera.

Table 3.2 A summary showing motorists who walked downhill and uphill

Test	**1**		**2**		**3**		**4**	
	Downhill	Uphill	Downhill	Uphill	Downhill	Uphill	Downhill	Uphill
Left	1-8, 16	9-15	1-9	10-17	1-8, 15	9-14	1,3,11	2,4,10
Right	1-9, 15-16	10-14	1-8, 16	9-15	1-7, 12	8-11	-	-
Test	**5**		**6**		**7**			
	Downhill	Uphill	Downhill	Uphill	Downhill	Uphill		
Left	1-6,13	7-12	1-10	11-16	1-9,18	10-17		
Right	1-9,16	10-15	1-11,18	12-17	1-10,18-19	11-17		

Of the 193 participating motorists 110 walked downhill and 83 uphill. The average walking speeds are shown in table 3.3 below.

Table 3.3 Average walking speed and standard deviation for motorists walking uphill and downhill.

	Downhill	**Uphill**
Number (persons)	110	83
Average (m/s)	1.34	1.39
STD Dev (m/s)	0.496	0.615

The average speed for those who walked uphill is 0.05 m/s faster than for those who walked downhill. A faster speed was expected for those who walked downhill than for those walking uphill. However, there is almost no difference at all and therefore the conclusion is that the slope of 4.5 % does not affect the walking speed when people evacuate.

3.2.7 Reaction on different announcements

In the tests two announcements were used. The first announcement, made after approximately 5 minutes was always the same, "explosion hazard". After another two minutes the second announcement was "leave the tunnel" or "leave the tunnel via the emergency exits".

In one test only, Test 6, there were still people in the tunnel during the second announcement. In the other tests, the tunnel was already evacuated before the second announcement.

Therefore no conclusions can be made about which of the alternatives of the second announcements that was most effective. Considering that the first announcement was effective (all participants found the exits), the adding "via the emergency exits" to the instruction “leave the tunnel” is probably not required.

In all tests most of the participants acted after the first announcement. The announcement confirmed that it was dangerous to stay in the tunnel. However, the time from the announcement until they started to act was different in the different tests.

3.2.8 Locking car

The proportion of people locking their car was 27% in Tests 1-7 and 24 % in Tests 8-9. Locking the car was sometimes widespread (50% did it in Test 2). However, this was not a main focus in the current study and therefore the data is not enough reliable. Still, there seems to be a great concern about how to leave the car and drivers need to be told what to do to shorten this decision time. More research is needed to make conclusions about this specific behaviour.

3.2.9 Other behaviour

There are several behaviours in the tunnel that could be the focus for studies in the future. Examples of this is how drivers leave their cars, drivers walking around in the tunnel without any apparent goal at all before they decide to evacuate and so on. To be able to quantify any such studies, however, more research is needed.

3.3 Discussion

Any scientific study should pay attention to the basic characteristics of validity and reliability. This is to ensure that the models used as well as the method and the experimental procedure provide the desired knowledge, and that similar studies provide similar results.

Validity in the road tunnel study is first and foremost a question about reality of the stage model. Does the human behaviour work like we have presumed when dividing it into stages 1-3 above, i.e. do people facing an accident first wait in their car, thereafter spend some time hesitating before starting to walk towards an exit?

The best answer to the question of validity is given from the analyses of occurred accidents. Both the Tauern and Mont Blanc tunnel fires (see Chapter 1), as well as the King’s Cross fire show that people facing an accident continue with what they were doing before the accident for quite a long time. People need confirmation that there is a real danger before they decide to act according to the danger.

The study of Canter 1990, where he tests people’s ability to predict fire growth rate, is of great importance for understanding why people do not react in time. It is clear that people underestimate the danger from a fire, and it is probable that people believe that they are safe in their cars for a longer time than what is the actual case during a fire in a tunnel.

The King’s Cross fire however, show that once people achieve information that they believe is true they act according to the given information.

The findings make it probable that the human behaviour undergoes stages where the first stage is characterised by a feeling of security and ignorance of the danger. People continue with whatever they were doing before the accident, then once they realise that something actually has happened they investigate it and only when they get some sort of confirmation of the danger they start evacuating.

A satisfactory reliability means that the same experiments made by anyone else provide the same results. The question of reliability is to a great extent a question of statistics, to proof that the sample is big enough and that the result do not depend of the people involved in the study.

In total nine tests were made, involving 193 persons. To ensure that the people involved in the study are representative for common road tunnel users a comparison was made between the people in the tests and people just using the tunnel an ordinary day. The conclusion from the comparison is that the people in the study are well representative for common tunnel users of the Benelux tunnel, (see Appendix A). However, no consideration was taken to the fact that the ordinary tunnel user of the Benelux tunnel may differ from other tunnel users. For example there was only one person in each car during the tests, there were no buses or trucks, and there were no disabled participants. Even though the test population is well representative for the studied case it is important to keep in mind that the specific population of any other tunnel must be analysed and compared to the test population before conclusions are made.

Also the type of tunnel and all other circumstances that may affect the outcome of an evacuation must be analysed and compared to the test circumstances before making conclusions about other tunnels than the Benelux tunnel.

The statistics presented in chapter 3.2 show that there is good reliability in all conclusions from the tests in the Benelux tunnel. It is important to underline that simply because all conclusions presented here show a great reliability, this does not mean that any conclusion derivable from this work necessarily has satisfactory reliability.

The purpose of Chapter 3, to determine the time spent in different phases from the moment that an accident occurs in a road tunnel until the moment that all people in the tunnel are brought to safety, is achieved with validity and reliability.

3.4 Conclusions

The purpose of the study was to model the times spent in different stages of an evacuation. Conclusions are presented about these times as well as their distribution. As usual, differentiation is made among the time lost before leaving the car, the time lost hesitating before abandoning the car, and the time required to walk to an emergency exit.

3.4.1 Group behaviour

A general conclusion is that the presence of other people affects the individual and results in group behaviour. As soon as someone reacts in a way that other people note, the behaviour spreads among a group. This is obvious in all stages; for example one motorist opening a car door results in other motorists opening their doors too.

This "herd" behaviour is reflected in the statistics of the different groups. During Stage 1 there are two discernible groups that react before and after the announcement is made. The group that reacts before the announcement is discernible into two more populations, one that reacts early and one that reacts later.

The conclusion concerning the group behaviour is that there will be a probability that any individual will belong to a certain population. Different populations have different statistical characteristics as mean value, standard deviation and distribution.

Based on the current data, the probability that an individual belongs to a certain group can be estimated, and used for future modelling. The probability that an individual belongs to Subgroup 1a is 9%; the probability that an individual belongs to Subgroup 1b is 9% again; and the probability that an individual belongs to Group 2 is 82%.

On the other hand, all participants in subgroup 1a come from the same test, i.e. Test 2, and it is concluded that the group behaviour is what made the motorists act. This makes it probable to believe that if no one reacts, the others will not act either. From this perspective there will not be any subgroups, but the probability that there are persons who react at an early stage is still 9%.

One effect of the group behaviour is that people with less information about the situation than others react earlier than they would if they were alone. For example some people in a tunnel maybe do not hear announcements because they listen to music. If they see other drivers open their car doors, they understand that something has happened and realise that they too ought to react. However, to make conclusions about this aspect of group behaviour more research has to be done.

3.4.2 Time to leave car

As described above, there are three discernible populations during this stage; two populations of people reacting before the announcement is made and one population reacting after the announcement is made.

Conclusions can, however, only be made about the distribution within the different groups since the distribution of people between different groups depend on the time when the announcement is made. Surely, if the announcement is made at an early stage everybody will be in the “after announcement”-group while if the announcement is made very late the group distribution will be the opposite. Still, if the announcement is made after 331 s, about 80 % will be in the “after announcement”-group. The overall distribution when an announcement is made after 331 s is:

$$X = (331+(0.816\ (GEV\ (-0.22; 19.91; 33.08))))+((1-0.816)\ 0.51\ (Norm\ (41.6; 17.1))+(1-0.51)\ (Gumb\ (28.8; 155)))$$

To be able to make conclusions on how the distribution between the different groups is affected by the time when the announcement is made more tests have to be performed. Such tests could be performed in the same way as the road tunnel tests in the Benelux tunnel, but with announcements made after for example 30 s, 100 s, et cetera.

3.4.3 Hesitation time

Conclusions about the hesitation time are made for the distributions in the different groups as well as for the time to leave car. As described above, the total test population is divided into two groups; with people reacting before or after the announcement is made.

The "before announcement" population is distributed as:

Hes(before) = 0.08 (hes = 0) + (1-0.08) Norm (151; 81)

The "after announcement"-population is distributed as:

Hes(after) = 0.28 (hes = 0) + (1-0.28) GEV (-0.44; 6.13; 8.42) s.

This again shows that it is advisable to make the announcement as early as possible; less time will be lost.

Another observation is that the proportion of motorists who acted with determination and *without* hesitation is larger in the *after announcement* group. We interpret this as an effect of better information; motorists lost less time because they were aware about the danger (better threat assessment). This is another reason for early announcements.

Still, even though early announcements seem to shorten the evacuation time, it is not possible to make any conclusion about the optimal timing for announcements, or any information, after an accident. To make such conclusions tests must be made where announcements are given at different times.

3.4.4 Walking speed

There is no significant differences in walking speed caused by affiliation to groups reacting before or after the announcement is made. Instead the conclusion about the walking speed is that it is a Gumbel distribution with the following characteristics:

Walking speed = Gumb (0.4431; 1.1185) m/s

The mean walking speed is 1.37 m/s. Other references, (e.g. Pauls 1988) tell that the walking speed varies between 1.2 m/s and 1.6 m/s. These values are taken in a horizontal plane and they can be compared to our results.

3.4.5 Difference in downhill and uphill

There is no difference in walking speed caused by the slope in the Benelux tunnel. The gradient of the slope is 4.5%.

3.4.6 Closest emergency exit

Three conclusions can be made about the choice of walking direction inside the tunnel:

- People do not want to pass a burning vehicle.
- If people have two exits to choose between, the closest one is almost always chosen.
- If people do not choose the nearest exit they go to next exit upstream in the driving direction.

3.4.7 Information

No conclusions have been made about information design and the consequences of different announcements for the evacuation behaviour or duration of different stages during the evacuation.

4 TRAIN TESTS

As a first step in collecting data on train evacuation, we studied the flow of people when leaving the train through the normal exits. Recordings have been made at 4 railway stations during normal operation; that is, with normal travellers not participating in a test or an exercise. Two other tests were planned evacuation exercises. Planned, that is, the participants knew what was going to happen. These recordings comprise the material of the present study. The material is limited. The evacuation never came as a surprise that required people to give up their original plans and activities; there was no uncertainty about where to go after leaving the train, etc.

For these reasons, the stage model of road tunnel evacuation is not applicable here. The train tests provide data on egress capacity, mainly as a function of door width and as a function of the vertical distance between the train floor and the platform. In addition, the effect of carrying luggage was studied.

4.1 Method

Video recordings were made at the following railway stations: Utrecht central, Schiphol, Best (all in The Netherlands), Kastrup (Denmark), and Stockholm (Sweden). There were two studies in Stockholm: an evacuation exercise executed in 1999 and reported earlier by Frantzich (2000) and a normal observation of disembarking passengers. A total of 978 people were observed exiting trains.

The video recordings were made from the platform with handheld cameras directed at the exit doors. In Best, videos of three fixed cameras of the closed circuit TV were used together with two handheld cameras. Flows were determined as follows.

- The timer started when the first person passed the exit; and stopped when the last person in a row passed the exit. If there was a pause in the flow of people it was counted as two different flows.
- A flow was defined as the number of persons passing through the exit divided by the duration of the flow.
- For each flow, the door width was determined (clear width, that is, without obstacles).
- For each flow, vertical distance between train floor and platform was determined.
- For the analysis, the different flows were weighted according to the number of people; for example a flow based on 20 people counts twice as much as a flow based on 10 people.

Below, the 6 different stations and their flow data are described, followed by a summary table. Thereafter, an analysis is presented on flow data as affected by (a) door width, (b) vertical distance and (c) luggage carrying.

4.1.1 Utrecht

Utrecht central station is a major hub through which many people pass every day. Most of the trains stopping at Utrecht central carry commuters from other cities in the Netherlands, but there are also a few international trains stopping at Utrecht every day. The videos of people leaving trains were recorded during rush hours 19th March 2003.

Twenty-two trains of 6 different types were recorded. The door widths varied between 0.73 m to 1.27 m, as shown in Table 4.1. The vertical distance to the platform was 30 cm throughout the tests.

In total 446 persons were observed, mostly commuters with briefcases or lightweight bags at most.

Table 4.1 Trains in Utrecht.

Train type	**Door width (m)**	**Vertical distance (m)**	**N trains**	**N persons**
Two-storey intercity train	1.27	0.30	10	193
One-storey intercity train	1.07	0.30	2	75
International train	0.90	0.30	3	21
Local train	0.88	0.30	5	121
Local train	0.77	0.30	1	17
Local train	0.73	0.30	1	19
Sum			**22**	**446**

4.1.2

Table 4.2 shows the average flow as the total disembarking time divided by the total number of people exiting.

Table 4.2 Flow results in Utrecht.

Train type	**Door width (m)**	**Flow (pers/s)**	**Flow (pers/s*m)**
Two-storey intercity train	1.27	0.788	0,620
One-storey intercity train	1.07	1.00	0,935
International train	0.90	0.538	0,598
Local train	0.88	0.761	0,865
Local train	0.77	0.739	0,960
Local train	0.73	0.475	0,651

Figure 4.1 Photo from the train in Utrecht.

4.1.3 Schiphol

Schiphol is the former name of the first airport of The Netherlands, now called "Amsterdam airport", and one of the busiest in Europe. Commuters as well as people travelling by plane from the airport go by train to Schiphol station. The recordings were made on the afternoon 20th March 2003. The station is located halfway a 5 km long rail tunnel.

Three trains of different types were recorded. The door widths were 107, 127 and 140 cm, as shown in Table 4.3 below. The vertical distance to the platform was 30 cm in all tests.

In total 47 persons were observed, mainly commuters and a few travelling with heavy baggage.

In the test with the one-story intercity train a few persons had heavy luggage but in the other tests there were only one or two that carried heavy luggage.

Table 4.3 Trains in Schiphol.

Train type	**Door width (m)**	**Vertical distance (m)**	**N trains**	**N persons**
Two-storey intercity train	1.40	0.30	1	16
Two-storey intercity train	1.27	0.30	1	16
One-storey intercity train	1.07	0.30	1	15
Sum			**3**	**47**

The flows are shown in table 4.4.

Table 4.4 Flow results in Schiphol.			
Train type	**Door width (m)**	**Flow (pers/s)**	**Flow (pers/s*m)**
Two-storey intercity train	1.40	1.143	0.816
Two-storey intercity train	1.27	1.067	0.840
One-storey intercity train	1.07	0.682	0.637

4.1.4 Best exercise

Best is a suburb of Eindhoven and a minor stop along a very busy north-south railway. The train station is situated at the northern end of a 2 km long tunnel.

The recordings were made during an evacuation exercise with cosmetic smoke filling the tunnel. The primary purpose of the exercise was testing and training of the emergency services rather than observing the flow of passengers. Test participants were aware of the test purpose. They carried no luggage. Demographic information about the test participants was not available and therefore it is not possible to make comparisons to the normal demographic distribution in the actual trains. From the video material it is evident that they were healthy and able bodied.

A closed circuit TV system monitored all exits, but because of the smoke only three of the cameras actually displayed anything. In addition, two train exits were recorded with handheld cameras. The smoke was no major problem because the distance from the camera to the exit was only a few metres.

The door width was 1.27 m as shown in table 4.5 below. The vertical distance from the train floor level to this lower situated platform was 70 cm. This is because people used the emergency platform inside the tunnel rather than the higher platform of the station.

In total 86 persons were observed.

Table 4.5 The train in the Best exercise.				
Train type	**Door width (m)**	**Vertical distance (m)**	**N trains**	**N persons**
Two-storey intercity train	1.27	0.70	1	86

The flows are shown in Table 4.6.

Table 4.6 Flow results of Best exercise.			
Train type	**Door width (m)**	**Flow (pers/s)**	**Flow (pers/s*m)**
Two-storey intercity train	1.27	0.729	0.574

4.1.5 Kastrup

Kastrup, the train station of Copenhagen Airport is located 8 kilometres southeast of the city centre. From Sweden as well as Denmark the easiest way to get to the airport is by train. The recordings were made in the morning on May 6, 2003.

Eight trains of 2 different types were observed. The door widths were 1.37 and 1.27 m; the vertical distance to the platform was 0.30, 0.50 or 0 m (see Table 4.7). The local trains have two different levels in the same train; one level that has no vertical distance and the other where the distance is 0.30 m.

A total of 169 individuals were observed, most of them travelled with lots of luggage. Once, a school class (about 30 children, estimated age 10-12 years) disembarked, with teachers organising the disembarking. This test was excluded in the subsequent analyses.

Table 4.7 Trains in Kastrup.

Train type	**Door width (m)**	**Vertical distance (m)**	**N trains**	**N persons**
One-storey intercity train	1.37	0.50	1	20
Local train	1.27	0.30 / 0	6	119
Local train	1.27	0.30	1	30 (school class)
Sum			**8**	**169**

The flows are shown in Table 4.8. The train with the school class is excluded.

Table 4.8 Flow results in Kastrup.

Train type	**Door width (m)**	**Flow (pers/s)**	**Flow (pers/s*m)**
One-storey intercity train	1.37	0.952	0.694
Local train	1.27	0.717	0.564
Local train (school class)	1.27	0.441	0.347

4.1.6 Stockholm

Stockholm, the capital of Sweden, has a metro system comparable to the ones of London, St Petersburg or Paris. During rush hours trains are crowded with commuters. In Stockholm the recordings were made on April 8 and 10 and on May 12, 2003, between 7 and 8 am.

Four trains of one type were recorded. Each of the two cameras showed three doors, i.e. six doors in all. The doors were 120 cm wide. There is no vertical distance between the platform and the train floor; the metro is designed for fast embarkation and disembarkation of large numbers of people.

A total of 77 persons were observed, all of them commuters going to their jobs with no baggage or briefcases only.

Table 4.9 The metro in Stockholm.			
Train type	**Door width (m)**	**N trains**	**N persons**
Metro train	1.20	4	77

The flows are shown in Table 4.10.

Table 4.10 Flow results in Stockholm.			
Train type	**Door width (m)**	**Flow (pers/s)**	**Flow (pers/s*m)**
Metro train	1.20	1.588	1.221

Figure 4.2 shows one of the four tests.

Figure 4.2 Photo from the metro train in Stockholm.

4.1.7 Stockholm exercise

Frantzich (2000) performed an evacuation exercise in the Stockholm metro in 1999. Participants evacuated from metro trains inside a tunnel and then walked to a nearby station. Most participants were employees of the Stockholm local traffic company, but no one worked in the tunnel. Two tests were carried out with the same participants. In the first test the tunnel was dark and the wagons were crowded. The only light came from the lighting in the wagons. During the second test the tunnel lighting was switched on and the wagons were not crowded. In the first test only two wagons were used and in the second test the people were spread in all 8 wagons in the train. In total 143 persons participated in the exercise.

In both the tests the train stopped between two stations and the participants were instructed to find refuge. The doors were 1.2 m wide. There was no emergency platform in the tunnel, and the participants had to jump down a vertical distance of about 1.2 m.

The flow through the door was 0.1-0.2 and 2 0.4-0.6 pers/s in Tests 1 and 2, respectively. The lower flows were when the people used an escape ladder.

Apart from the fact that participants had practised evacuation before, Test 2 is similar to the Best exercise; both groups of participants were familiar with the surroundings already.

Table 4.10 The results from the evacuation exercise in Stockholm.				
Test	**Door width (m)**	**Vertical distance (m)**	**Flow (pers/s)**	**Note**
1	1.20	1.2	0.1-0.2	No light in tunnel
2	1.20	1.2	0.4-0.6	Light in tunnel

4.2 Analysis and results

The analysis was aimed at quantifying factors influencing the flow of passengers through the train exits. In particular, it was investigated whether the flow depended on (a) door width, (b) vertical distance, and (c) luggage carrying.

The relationships between flow and door width and flow and vertical distances were studied with (linear and exponential) regression analysis with R^2 as a measure of goodness of fit. R^2 varies between 1 and 0 and indicates how good the flows estimated from the regression model correspond to the actual flow values.

The relationship between flow and luggage carrying was investigated with a numerical comparison.

Flow depending on combinations of the factors is also discussed.

4.2.1 Door width

To estimate how the flow depends on door width, the results from Utrecht and Schiphol were used. All trains had the same vertical distance, the same type of travellers, the same density of people and a large number of observations. The mean flow and the total number of persons in each sample are shown in table 4.11 below. The total number of persons is 462.

Table 4.11 The flow (pers/s) for different door width.					
Test location	**Door width (m)**	**N persons**	**N tests**	**Time (s)**	**Flow (pers/s)**
Utrecht	1.27	209	10	260	0.804
Utrecht	1.07	75	2	75	1
Utrecht	0.88	121	5	159	0.761
Utrecht	0.77	17	1	23	0.739
Utrecht	0.73	19	1	40	0.475

Figure 4.3 and Table 4.12 show the results. The Chi-square test shows that the R^2-value was as low as 0.13 for a correlation in Figure 4.3.

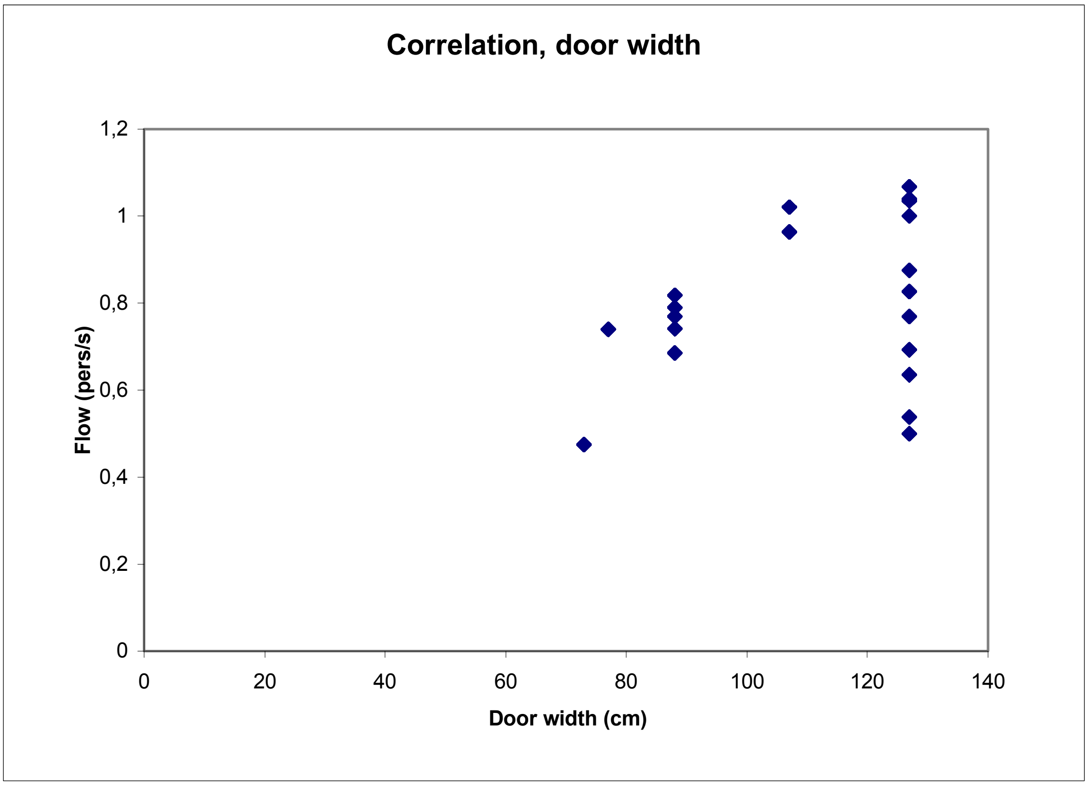

Figure 4.1 The different train disembarking tests.

The R^2-values are generally low, 0.13 at most, which does not indicate a relationship. The flow is almost the same for a train with 1.27 m wide doors as for a train with 0.88 m wide doors. This issue will come back in the discussion.

Table 4.12 The regression of door width on flow.

Type of correlation	**R^2-value**	**Equation**
Linear correlation	0.1292	$y = 0.0034x + 0.4711$
Exponential correlation	0.1048	$y = 0.5309e^{0.0039x}$

4.2.2 Vertical distance

To estimate how flow depends on the vertical distance, the results from Stockholm, Utrecht, Schiphol, Best exercise and Stockholm exercise were used, see Table 4.13.

Table 4.13 The flow (pers/s) at different vertical distances.

Test location	**Vertical distance (m)**	**N persons**	**N tests**	**Time (s)**	**Flow (pers/s)**
Stockholm	0	77	4	48.5	1.59
Utrecht. Schiphol	0.3	209	11	260	0.80
Best exercise	0.7	86	1	118	0.73
Stockholm exercise	1.2	20	1	40	0.5

The results are shown in Figure 4.2 and Table 4.14.

Table 4.14.The regression of vertical alighting distance on flow.

Type of correlation	**R^2-value**	**Equation**
Linear correlation	0.4103	$y = -0.8762x + 1.3088$
Exponential correlation	0.4292	$y = 1.2543e^{-0.8696x}$

There is a trend that the flow decreases as the vertical distance between the train and the platform (or ground) increases. R^2-values of 0.41 and 0.43 reveal a weak correlation. The conclusion is that we cannot say for sure that the flow depends on the vertical distance but what we can say is that there is a clear trend that the flow increase when the vertical distance decrease and vice versa.

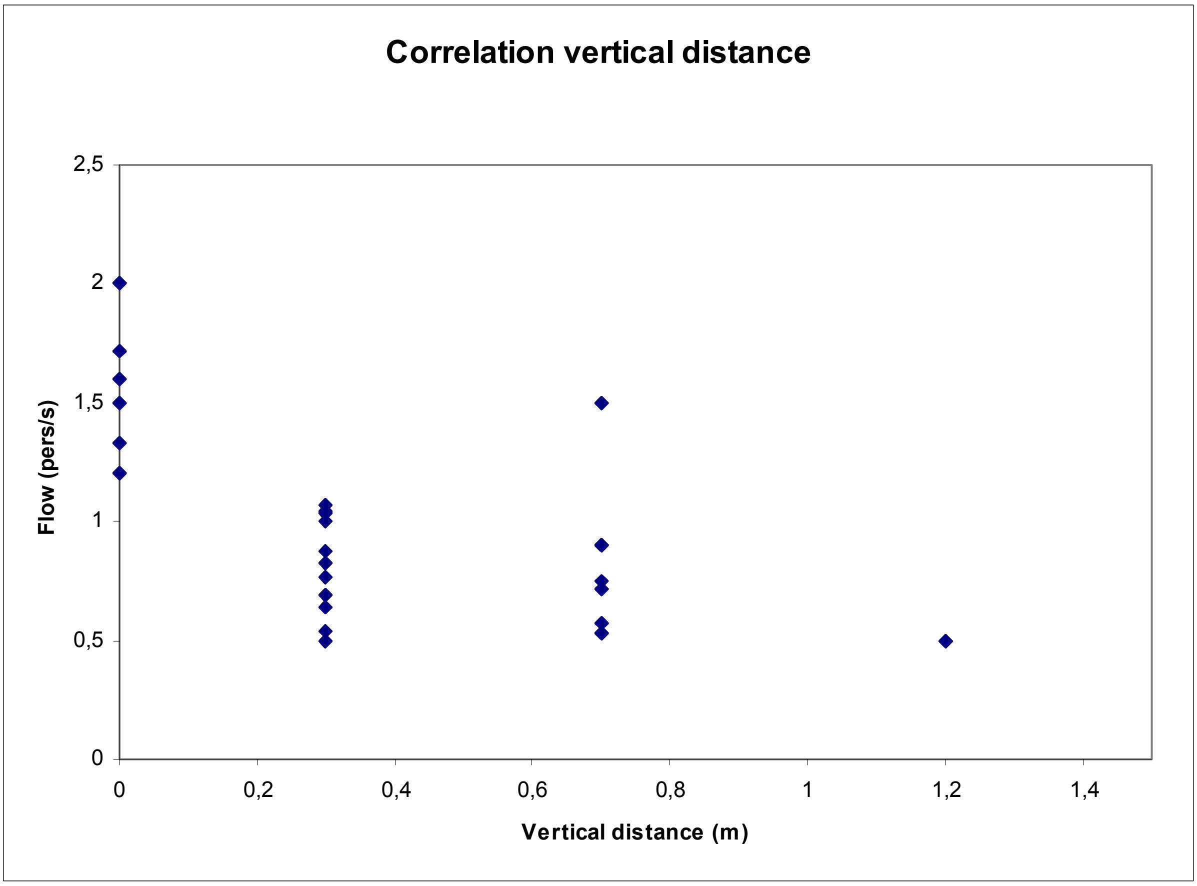

Figure 4.2. The different tests in the analysis.

4.2.3 Luggage carrying

Regression analysis was not used to study the effects of luggage carrying because luggage carrying was a dichotomous variable; people carried, or carried not, heavy luggage.

To estimate how flow depends on luggage carrying, the results from Kastrup, Utrecht Station and Stockholm were used. All trains had door widths between 1.27 and 1.30 m, which are to be considered as functionally equivalent. Some Kastrup and all Utrecht trains had a vertical distance of 0.3 m. All other trains were without vertical distance.

Inspection of the data reveals that the vertical distance affected the flow. Without vertical distance, heavy luggage reduced the flow to 50% of the flow value without luggage. When there was a vertical distance of 0.3 m, the reduction in flow was 33% only.

No correlation analysis can be made. The effect of heavy luggage was that that the flow decreases with at most 50%.

Table 4.15 The flow in the analysed tests with and without luggage.

Test	**N persons**	**Luggage**	**Flow (pers/s)**	**Vertical distance (m)**
Kastrup	44	Luggage	0.90	0
Stockholm	77	No luggage	1.59	0
Kastrup	75	Luggage	0.64	0.3
Utrecht	209	No luggage	0.80	0.3

4.2.4 Combination of the factors

Above, all the three factors door width, vertical distance and luggage have been analysed. There could also be combinations of them.

The possible combinations are:

1. Door width x Vertical distance
2. Door width x Carrying luggage
3. Vertical distance x Carrying luggage
4. Door width x Vertical distance x Carrying luggage

The tests that could be used to compare both vertical distance and door width are Stockholm (1.3 m wide and 0 m vertical distance), Utrecht (0.73-1.27 m wide and 0.3 m vertical distance), Best exercise (1.27 m wide and 0.7 m vertical distance) and Schiphol (1.07-1.4 m wide and 0.3 m vertical distance). In those tests the door width is about 1.3 m, except for some tests in Utrecht and two tests in Schiphol. In those tests the vertical distance is 0.3 m.

The data from the tests do not allow a combined analysis. The result from such an analysis would simply not be reliable, since there was no found correlation between different door widths; the r^2-value was at most 0.13. This means that all the combinations with door width as one of the factors automatically have very weak correlation, i.e. almost none.

The tests that are made with luggage all have door widths that do not vary. (One test has 1.37 m instead of 1.27 but this is almost the same value.) This means that no conclusions can be made about the combinations that contains both luggage and door width, i.e. 2 and 4.

For the combination Vertical distance x Carrying luggage, 3, the Kastrup tests are compared to the Utrecht and Stockholm tests, see Table 4.16.

Table 4.16 The flow in the analysed tests with or without luggage.				
Test	**N persons**	**Luggage**	**Flow (pers/s)**	**Vertical distance (m)**
Kastrup	44	Luggage	0.90	0
Kastrup	75	Luggage	0.64	0.3
Stockholm	77	No luggage	1.59	0
Utrecht	209	No luggage	0.80	0.3

When people carried luggage the flow increased with 40 % as the vertical distance decreased from 0.3 meters to 0. The corresponding flow without luggage increased with 99%. The result is that the flow increases more when people have no luggage than when people carry luggage as the vertical distance decrease. We come back to this issue in the discussion.

4.3 Discussion

In any scientific study attention should be paid at the basic characteristics of validity and reliability. This is to ensure that the models used as well as the method and the experimental procedure provides the knowledge that is searched for and that similar studies provide similar results.

Validity in the train study is first and foremost a question about reality of the evacuation behaviour. Do people disembark in the same way during a real fire as they do in the recordings?

There are no good studies of people disembarking from trains during real fires and therefore no comparisons to such circumstances can be made. Still, the results from the studies of people disembarking from trains make it unlikely to believe that the flow during a fire or after an accident should differ from the experimental values. There are several reasons for this conclusion.

The people that are disembarking in the train tests maybe do not encounter the same stress caused by the accident as they would in e.g. a real fire. Still, it is clear that people disembark as fast as they can, simply because they are aware that there are many people waiting right behind them. In metro systems (during rush hours especially) there is no doubt about the fact that people disembark as fast as possible and if anybody is blocking the door opening or disembarking too slow he or she is pushed out of the train.

The people inside the train decide to evacuate already when they are seated. Other people walking by in the aisle with the apparent goal to disembark affect many of them. Also, the passengers may be guided by instructions from the driver, telling them to evacuate the train.

Whatever the causes are, once people disembark through the exits they are in the same behavioural stage in the tests as in a real situation, i.e. evacuation stage (compare to stage 3 in the model discussed in chapter 3). Therefore we believe that the validity in the tests should be satisfactory.

A satisfactory reliability means that the same experiments made by anyone else provide the same results. The question of reliability is to a great extent a question of statistics, to proof that the sample is big enough and that the result do not depend of the people involved in the study.

A very significant number of people disembarking from many different trains in several countries have been evaluated. Comparisons are made between different test settings to see how different factors affect the flow. The large number of participants from different types of trains ensures that the results do not depend on the people involved in the study. We believe that this makes the statistics reliable and that the same results will be achieved again if anyone performs similar tests.

The purpose of Chapter 4, to determine the flow from train doors depending on the type of train, is achieved with validity and reliability.

The flow through train doors is almost the same from trains with 127 cm wide doors as from trains with 88 cm wide doors. One theory behind this result is that there are bottlenecks earlier in the train wagon that reduce the flow. In many train wagons the space in the aisle between the seats are often lesser than the door width and therefore the width of the train doors are not what reduces the flow. The normal long-distance trains are not designed for fast disembarking; the space is used to make comfortable seats instead of making the aisles wide as in metro trains that are designed for fast disembarking and not as much for comfort.

In most trains people stand close to each other when they disembark. In many trains they also step out side by side. When carrying luggage the distance between the people increase and there are no space enough to disembark side by side. This could explain why the flow decreases when people carry luggage. Another explanation is that people move slower when they carry heavy luggage because of the weight of the luggage. Therefore, the maximum flow when people carry luggage is much lesser than when not carrying luggage. The vertical distance is then not the primary factor to consider. The maximum flow with luggage is approximately 1 pers/s with no vertical distance.

Still, the vertical distance between the train and the platform is the most important factor. A train with no vertical distance and people with luggage results in a faster flow from the train than trains with a vertical distance of 30 cm where people disembark without luggage.

No comparison has been made between the studied population and the population that ordinary use trains. In all tests the studied population consisted of healthy people having no problem disembark the train, but old people or physically disabled people would probably cause a lower flow. Furthermore, although several different types of trains have been studied it should be kept in mind that the test results are limited to these types of trains.

In the Stockholm exercise likely reasons for a faster flow in the second tests are (a) light in the tunnel, (b) participants evacuated for the second time, (c) the train was less crowded, (d) any combination of the previous three reasons.

4.4 Conclusions

The best situation for train disembarking is no vertical distance at all. The results from the tests show that the flow is twice as high with no vertical distance as with a vertical distance of at most 0.7 m. With larger vertical distances, the flow is even lower.

For vertical distances exceeding 2 m it is however probable that completely different models should be used since people risk getting severely injured as they jump from the train. Furthermore, such distances are not of interest for a train evacuation study since the distances are above what is found in any train type.

Evacuations from trains should have no vertical distances at all to run as fast as possible.

The train door width is not of great importance for the flow from the trains in this study. This is because there are bottlenecks earlier in the trains that are smaller than the door. The conclusion is that it is the design of the interior of the train that determines the flow.

If the disembarking people carry luggage the flow through the doors becomes lower. The biggest difference is when there is no vertical distance. The flow is then twice as fast when the travellers carry no luggage. With a vertical distance of 0.3 m the travellers without luggage is only 25% faster. The conclusion is that people carrying luggage do not move very fast but they move faster than people not carrying luggage but who must step down a vertical distance of 0.3 m. This conclusion underlines the fact that the vertical distance is the most important factor to consider when designing for faster disembarking from trains.

5 EVALUATION AND RECOMMENDATIONS

The purpose of Chapter 5 is to compare the conclusions made in Chapter 3 and 4 to what is already known from earlier studies and described in the literature review in Chapter 2. Also, recommendations about actions that would fasten the evacuation process will be made.

When giving recommendations about how to make the evacuation process run faster, the main focus is not in quantifying the effect of certain actions but sooner to provide an understanding for the extent in which different factors affect the evacuation.

Both road and train tunnels are considered in this chapter. The structure of this chapter is to discuss topic by topic and compare test conclusions to literature findings.

5.1 Evaluation

5.1.1 Stage model

The last decades several models describing the human behaviour during accidents have been presented. Most of the models, which are summarised in Chapter 2, are based on different stages that the human mind undergoes during an accident.

While these models are the theoretical results of decades of research in the field of psychology, what is needed in this study is first and foremost a pragmatic model that is easy to quantify and can provide empirical data. The meaning of a model that is easy to quantify is that the different stages of the model should be discernible and that it should be able to provide theoretical distributions. Most important of course, is that the model is close to the reality.

The behavioural model of Passenier & van Delft (1995) was used to define the discernible stages in Chapter 2. However, instead of the four stages of this model only three stages were used, because not all actions in the four-stage model are possible to observe. What is achieved is a model that corresponds to the model of Passenier & van Delft but the starting point is how a spectator sees the course of events.

An evaluation of the appropriateness of the model to the actual behaviour is best judged by the observed behaviour of the participants in the tests. Do people act according to the model, or are there a significant number of exceptions? I.e. is it possible to describe people's behaviour by the three-stage model or do people act otherwise? What was found in the analysis and revealed by the results in Chapter 3 (see Appendix A for details) was that very few acted in a way that do not correspond to the three-stage model. Most people sat in their cars, then stepped out and hesitated for a while and finally decided to evacuate. The stages are well discernible.

Also, the statistical analysis display that people's actions are very well described by theoretical distributions. This gives even stronger confidence to the conclusion that the used model in comparison to the results from findings about human behaviour is close to the reality.

5.1.2 Panic

This study confirms the theoretical thesis that panic is exception rather than the rule in evacuations. There were no signs of either individuals or groups of people becoming panic stricken in the different tests. On the contrary most people acted well planned and even though some people were running to the exits in the road tunnel tests they did not display the non-social behaviour that characterises panic. These conclusions are similar to the findings of e.g. Sime, discussed in Chapter 2.

5.1.3 Group behaviour

Group behaviour is said to be the effect on the individual's behaviour of surrounding people. In reports from e.g. Sime (1995) this is said to be a factor that affects the individual's behaviour and therefore should be considered in the design of evacuation systems.

In this study the group behaviour has been evaluated from a statistic approach. The results underline the importance of the group behaviour. It is obvious that the visible actions taken by other drivers is what makes people react in the earlier stages of the model; i.e. a driver stepping out of his car makes other drivers copy this behaviour.

The group behaviour in evacuations from trains should pay an important role too, but in this case the behaviour is more expected and have not been the focus for studies in the same way as in the road tunnel case. The early stage that includes decision-making takes place inside the train and the effect of the group behaviour is harder to study. Still, it is likely to believe that the surrounding people in a large extent affect the individual inside trains too.

5.1.4 Information

Information is needed in all the different stages from the moment that any accident is a fact until all people are safe. Several reports have been published that presents conclusions about the need for information in different stages as well as how the information should be designed. See Chapter 2 for more details about reports from Canter, Keating, Proulx and Sime.

In this study conclusions have been made about the effect of information given as spoken messages via loudspeakers in the road tunnel. The information design is not evaluated since only one message is possible to study. (See Appendix A for details about the message).

The conclusions coincide with conclusions from other reports saying that information is of crucial importance for the evacuation process. Most people react and step out of their cars after the announcement is made. People reacting after the announcement also spend less time hesitating than those reacting before the announcement is made. It is clear that the information provided fastens the evacuation process and provides a guiding that is needed.

5.1.5 Walking speed

The average walking speed achieved in this study is 1.37 m/s. This walking speed is achieved from dividing the distance each person walks by the time this takes.

When comparing the walking speed presented in this report to values of walking speed given in other reports it should be kept in mind that the surroundings of the study as well as the method used for calculating the walking speed may differ from studies and explain differences between values. In this study the walking speed is calculated for individuals evacuating in tunnels where other people are present. For example people evacuating alone from apartments may be affected of totally different factors resulting in different values of walking speed.

5.1.6 Vertical distance

This study has evaluated the effect on the flow of people through train exits caused by the vertical distance between the platform and the train floor level. Even if there is no explicit statistical relation proven between vertical distance and flow the findings reveal that this is one of the most important factors, more important than for instance door width.

The effect oh the vertical distance should be compared to the general impressions from the evacuation experiments performed by Frantzich (2000) in Stockholm Metro, where people evacuated from metro train inside a tunnel. (See Chapter 4 for details.) The effect of the vertical distance was not studied in a quantified way here, but still it is evident that the effect from this rather large vertical distance was of great importance.

However, other references of walking speed give similar values, for example Pauls (1988) concludes that the walking speed varies between 1.2 m/s and 1.6 m/s. These values are taken in a horizontal plane and they can be compared to our tests.

5.2 Recommendations

Recommendations about actions that provide a faster evacuation process can be given based on the conclusions from the experimental tests and comparisons between these conclusions and findings presented in the reports discussed in Chapter 2.

5.2.1 Information

The conclusion from the road tunnel tests is that the announcements given via the loudspeakers are what make most people decide to evacuate.

The recommendation is to provide information as early as possible to help people decide what to do and to make people react at an earlier stage.

With informative messages given rapidly it is clear that the evacuation process would run faster. It is necessary to pay attention to the information system in the daily use too, to ensure that the public can perceive and understand the information provided by the communication system when it is in daily use. It is essential to build up a climate of confidence.

5.2.2 Group behaviour

The group behaviour among the people in the road tunnel experiments was found to play an important role in the evacuation. This is not only a fascinating fact but also something that should be kept in mind when planning for evacuations.

There are several possibilities for how to take advantage of the group behaviour. Firstly, general information should be given to the public about the good effects of the presence of others. It should be underlined that people facing a fire inside a tunnel form a group.

When there is a fire inside a tunnel the surroundings soon will be very disadvantageous. Fans for smoke evacuation will create much noise and the fire may produce lots of dense smoke. This will make it hard to reach through to the people stuck in the tunnel with visual as well as audible information.

One way of giving information is to use the radio frequencies, to simply give information to people who are listening to their car radio. Of course only some of the car drivers will be listening to the car radio, but if we consider the group effect this gives us a powerful tool to guide the people in the tunnel. People should be told to make others aware about what to do and how to do it.

Most people who are not listening to the radio will have realised that something has happened but they do not know how to interpret the situation. This is known from several earlier studies, see Chapter 2 for reports of e.g. Canter. These are the ones that first will act according to the group behaviour, when they see how others react they will follow. The same pattern is seen in many other contexts where groups of people are gathered, not only evacuations, e.g. people crossing roads when there are no cars but the traffic light says “don’t walk”, et cetera.

5.2.3 Tunnel exits

Bottlenecks appeared in front of the tunnel emergency exits in several of the road tunnel tests. This is clear evidence that there either should be more exits in the tunnel or that the existing exits should be designed to allow a faster flow. The doors in the Benelux tunnel have sills of approximately 0.3 m and a horizontal depth that also makes the flow slow down.

Based on this study it is not possible to give any recommendations about how the exits should be designed or how large the internal distance between two doors should be. It is though important to underline that this is where the bottlenecks appear and therefore it is important to ensure that the design and number of doors allow a fast enough flow of people before constructing any tunnel. Of course the highest possible flow through the doors should be compared to how many people that are believed to be in the tunnel at the same time, and therefore such analyses should be done each time a tunnel is designed.

5.2.4 Vertical distance

The vertical distance between the platform and the train floor level was shown to affect the flow through train doors in a large extent. The lesser the distance, the faster the flow will be.

Based on the conclusions about the effect of the vertical distance it is possible to recommend platforms to be constructed inside tunnels too, of the type that was seen in the Best railway tunnel experiment (see Chapter 4 for details) for example. There is an obvious difference between the flow through the train doors in this tunnel experiment compared to what was seen in the tunnel experiment performed by Frantzich in the Stockholm metro (see Chapter 4 for details) where there was no platform at all.

6 MODELLING

The aim of the first part of the study was to collect data about the different stages of the evacuation from road and train tunnels. Such data is important for understanding of the influence of different stages on the total evacuation time. It also provides a possibility to model the total evacuation time in a given case which is important not only for making a total evacuation time of separate parts, but also for understanding the process. It should however be kept in mind that any data used for modelling is limited to similar circumstances as those who characterised the occasion when the data was collected. Hence, the validity of the conclusions is limited when modelling of evacuations that are not equal to the evacuation where data was collected takes place.

6.1 Case study: evacuation from the Benelux tunnel

We now present an example on how to use the data for modelling evacuation of a tunnel. The focus of the model will be the Benelux tunnel where data was collected and presented in the earlier chapters of this study. The theory is the same as was used when collecting data for the road tunnel tests, i.e. based on observable behaviour.

Our model of evacuating a road tunnel consists of a walking stage preceded by two "psychological" stages. Before the walking stage, there is a stage in which motorists decide to leave the car. This stage ends with a "go"-decision. Before the decision to leave the car behind, there is a stage in which motorists decide to get out of their car. Because this is the first observable sign that motorists are aware that this is a peculiar situation, we can call this stage "reaction time", "awareness stage", or time to wake up to the situation. Figure 6.1 shows the three stages.

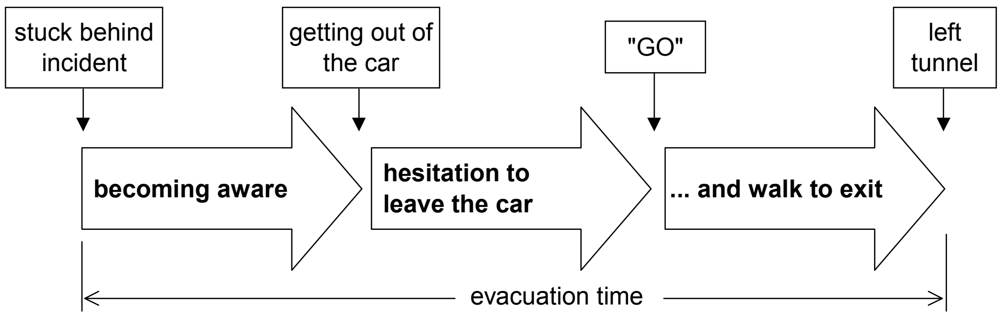

Figure 6.1 Three-stage model of a motorist who leaves a tunnel afoot after being stuck behind a burning HGV.

Figure 6.2 shows the model as an event tree. Starting from the left, three branches represent respectively two populations that get out the car before there is any loudspeaker announcement and one population that needs loudspeaker announcements to wake up; associated probabilities 0.82 and 0.18, respectively. Each of these three branches continues with two further branches, representing motorists who do not hesitate and motorists who hesitate for some time before deciding to go; associated probabilities 50-50. Finally all branches end with one and the same branch: walking time, the product of walking speed and distance to the nearest exit.

The model makes clear that psychological stages of awareness and decision increase the time required for evacuation. More simple models based on walking time alone are clearly incomplete, and will underestimate the time required for evacuation.

More complete assumptions of the model are:

- Evacuation requires walking the distance to the nearest exit. The distribution of walking speed is specified; time required is the product of walking distance and walking speed.
- When selecting the nearest exit, motorists ignore the exit beyond the incident.
- Before the walk, motorists may lose time hesitating to make a "go" decision.
- Before the hesitation to go, motorists have to decide to get out of the car ("awareness time").
- Motorists are either "passive" or "action prone", associated probabilities 0.82 and 0.18, respectively. Action prone motorists become aware (and get out of their car) within 100 s or with a delay of 100 s at least, associated probabilities 50-50; each group with its own distribution (two distributions of wakeup time). Passive motorists need announcements of the tunnel operator to become aware about the situation (a third distribution of wakeup time).
- The moment of the operator announcement is an important determinant of evacuation time, because most motorists (82%) will wait in their cars for that announcement.
- Action prone motorists are either of the "hesitation type" or the "nonhesitation type", associated probabilities 0.92 and 0.08, respectively. Nonhesitation types don’t lose any time - they "go" immediately. Passive motorists are also of the "hesitation type" or the "nonhesitation type", but the associated probabilities are 0.72 and 0.28, respectively. The model specifies the distribution of the time required for hesitation time. Motorists of all types have the same distribution, except for passive hesitating motorists who have a special distribution.

When calculating possible times for an individual inside the road tunnel the total time is achieved by following the event tree from the beginning to the end, by determining times for every branch. The total sum is achieved by adding the times achieved from the different branches.

For a group of people it is necessary to simulate the course of events. This way people will follow every branch and achieve times in every stage according to the distributions. The total evacuation time for a group of people will be determined by the longest time achieved by an individual. Such simulations need computer modelling to be able to simulate groups of people.

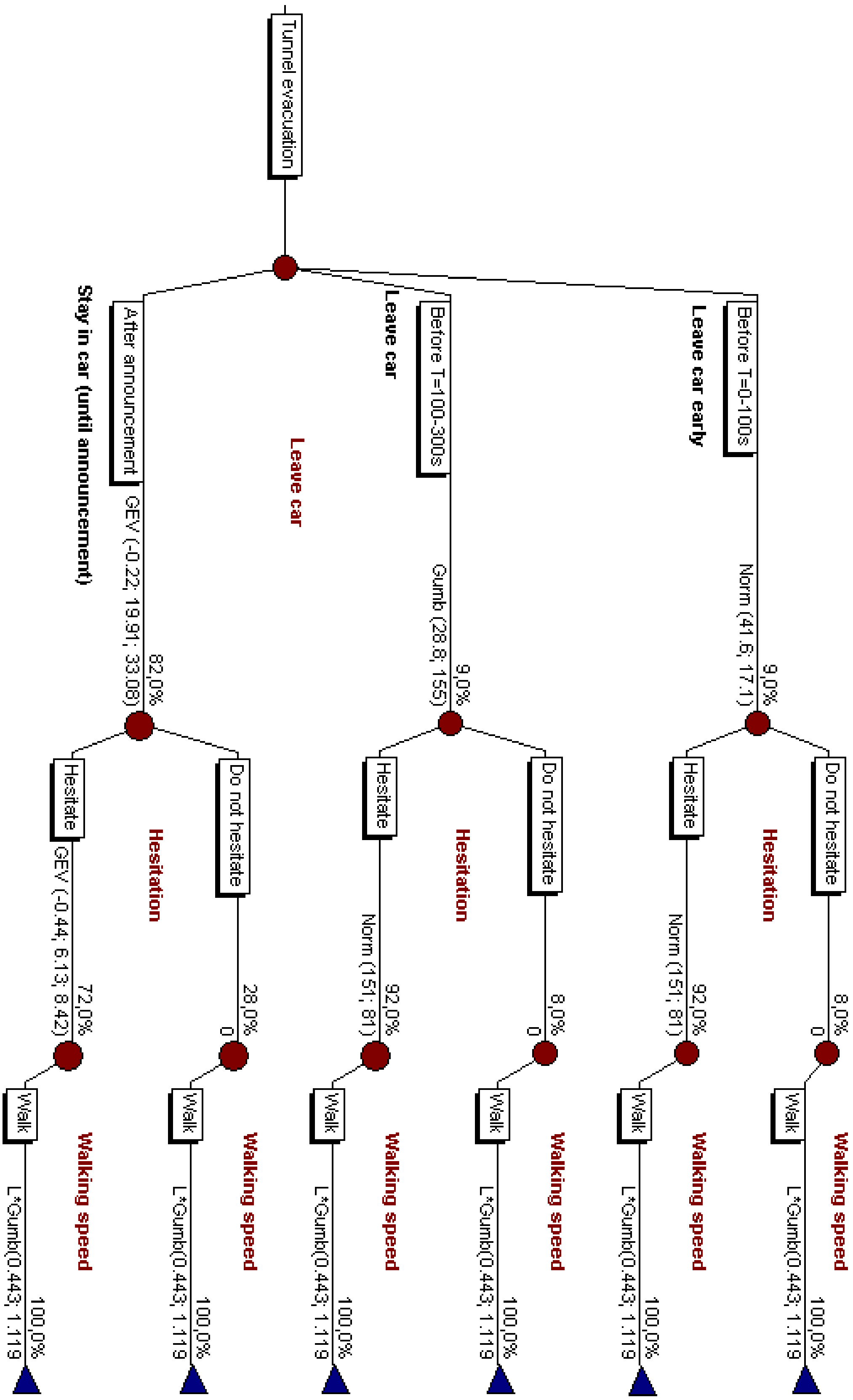

Figure 6.2 Event tree describing evacuation from a road tunnel.

6.2 Example

To illustrate application of the model, we modelled a group of six imaginary motorists; two being aware almost immediately, two becoming aware with some delay, and the other two becoming aware after the announcement of the operator. Also, a Mr. Fast reacting as fast as possible and a Mr. Slow reacting very late are added for comparison. The distances the motorists 1-6 had to walk to the nearest exit were chosen randomly. In many tunnels the distance to the emergency doors are longer than 100 meters. We added Mr Fast and Mr Slow to the group, representing the fastest and the slowest walking times. For Mr. Fast and Mr. Slow, the distances to the nearest exit were set at 100 m. This results in different times on every stage for all eight modelled persons. In Table 6.1 the achieved total evacuation times as well as the time spent on every stage are shown for all eight modelled motorists, based on the data collected in the Benelux tunnel.

Table 6.1. Evacuation times of some (imaginary) motorists. (The tunnel will be empty after 1109 s or 19 minutes; persons 5 and 6 need the announcement of the operator that comes after *331* s).

Person	**Leave car (s)**	**Hesitate (s)**	**Distance to exit (m)**	**Walking speed (m/s)**	**Walking time (s)**	**Total evacuation time (s)**
1	40	0	20	2.2	9	49
2	65	228	150	1.65	90	383
3	193	82	54	1.37	39	314
4	142	0	68	0.82	83	225
5	*331*+30	18	111	1.05	106	362
6	*331*+130	0	12	1.45	8	469
Mr. Fast	14	0	100	3.27	31	45
Mr. Slow	547	161	100	0.38	263	1109

The graphs below show the positions of motorists 1-6, Mr. Fast and Mr. Slow in the distribution of each stage. The first graph shows pre-announcement stage 1, the second graph shows pre-announcement stage 2, third graph shows those reacting after the announcement.

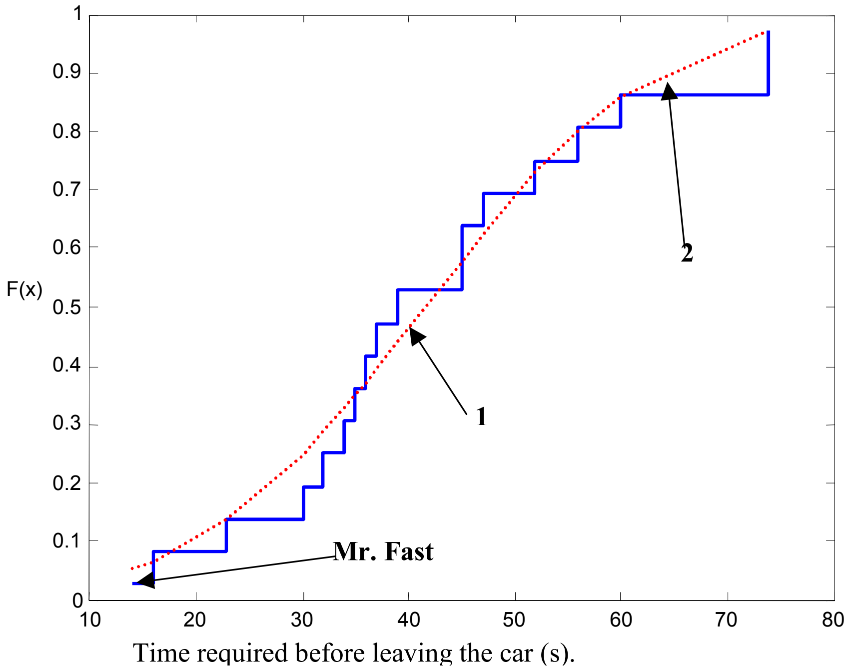

Figure 6.3. Awareness time for 1, 2, and Mr. Fast. (All reacting before the announcement.)

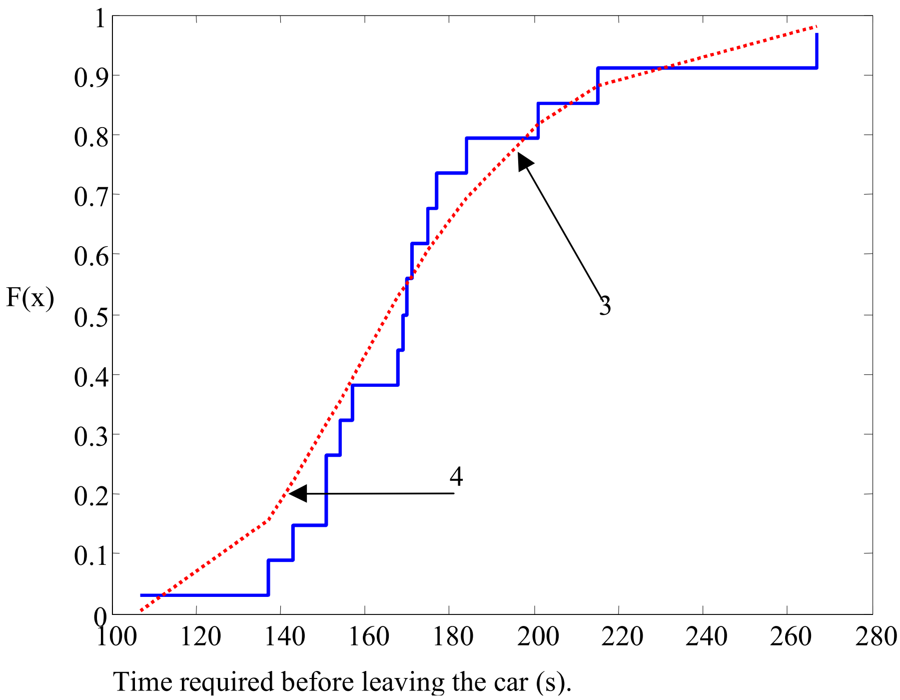

Figure 6.4 Awareness time for Motorists 3 and 4. (All reacting spontaneously, before the operator's announcement but after those in figure 6.5)

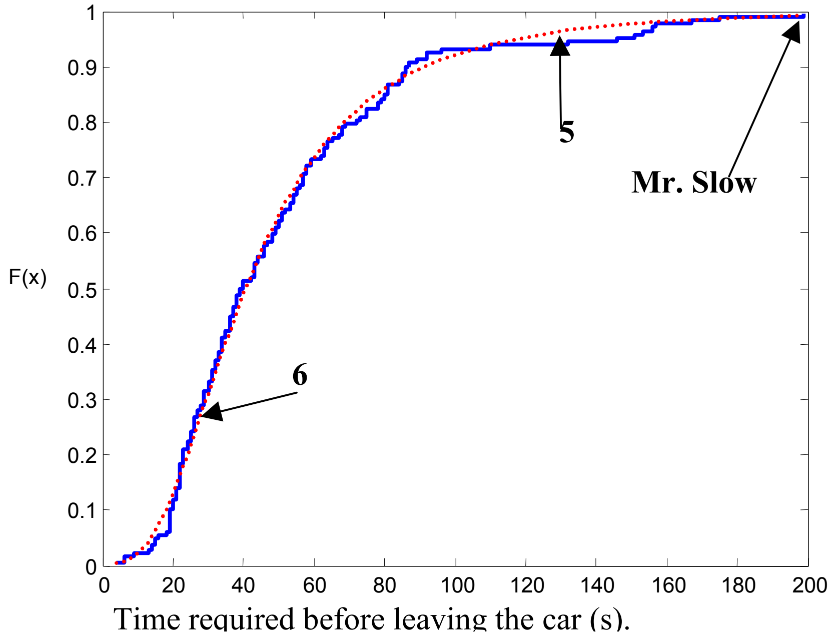

Figure 6.5 Awareness time for Motorists 5, 6, and Mr. Slow, all requiring the operator's announcement to get out of the car.

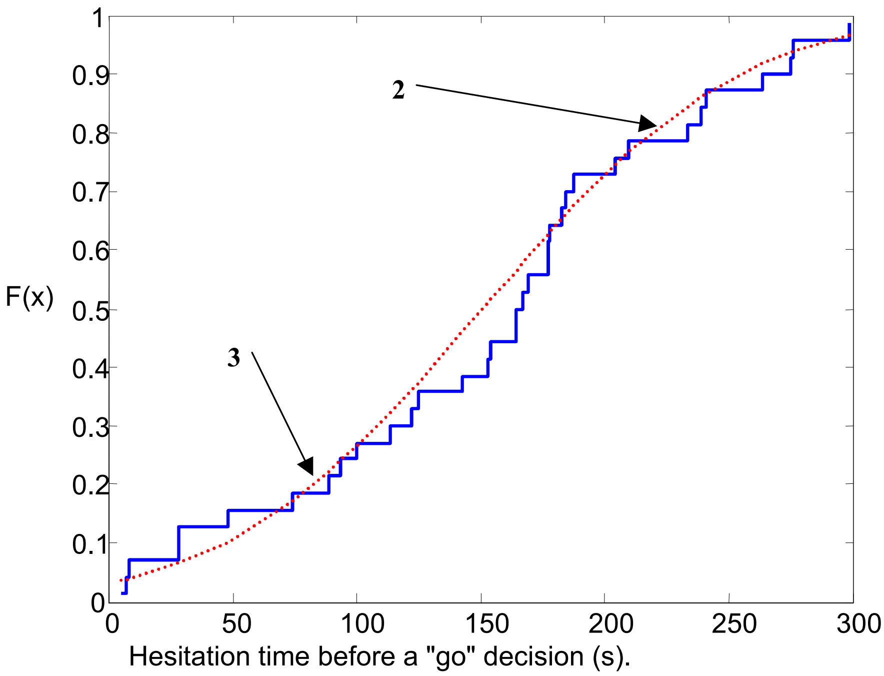

Figure 6.6 Time required for a "go" decision for Motorists 2 and 3. (Both needed the operator's announcement.)

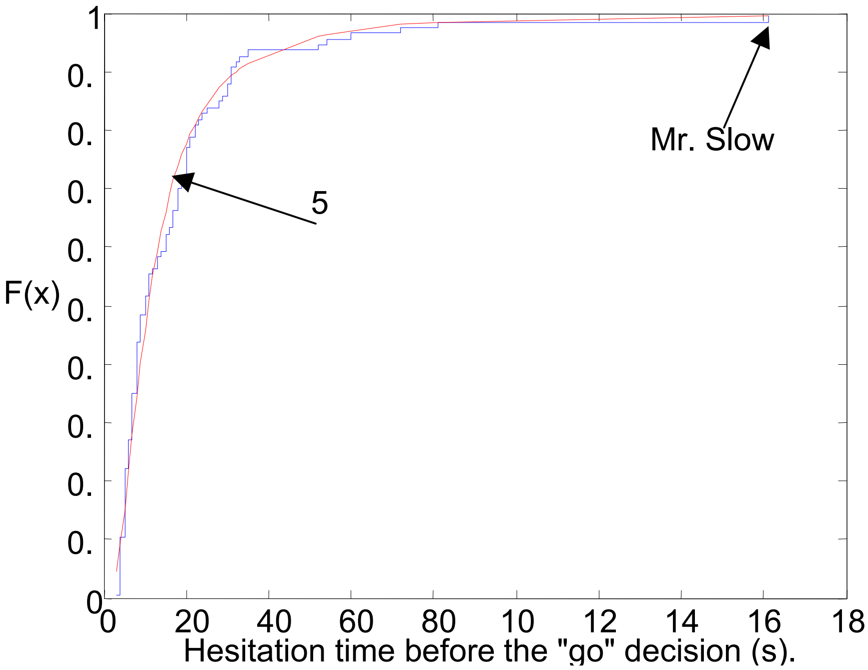

Figure 6.7 Time required for a "go" decision for Motorist 5 and Mr. Slow. (Both needed the operator's announcement.)

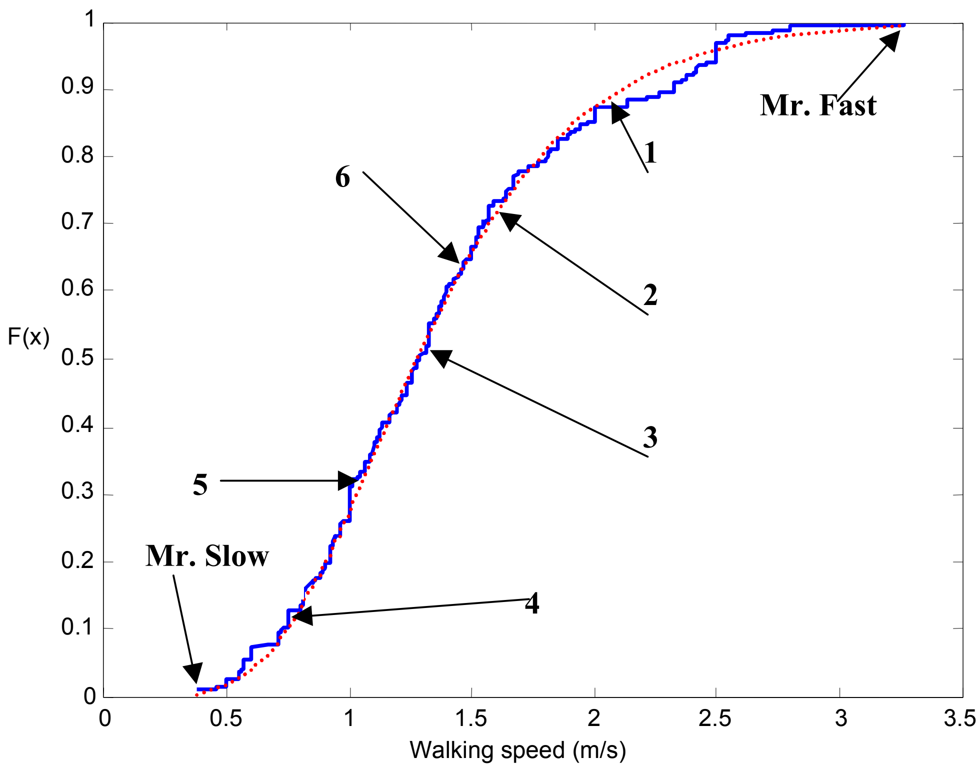

Figure 6.8 Walking speeds of all 8 motorists.

6.3 Discussion

The model can be used to depict the evacuation of larger groups of motorists. The model can also be used for a worst-case scenario analysis, as the current "Mr. Slow". The thus obtained evacuation times can be compared to the time available to answer the critical question whether there is sufficient opportunity to evacuate. Time available depends on the scenario and the escalation of the incident. Smoke and heat are generally tolerable during the first minutes; and forced ventilation activated by the operator (or by fire sensors) may carry smoke and heat away.

The model can also be used to depict the effects of timely operator intervention. If the operator makes early announcements (at, or slightly before, 100 s), the second branch of the event tree becomes void, and all passive motorists will start to get out of their car, 28% will directly proceed to the nearest exit, etc.

The results of the analysis said that the motorists need some sort of information from the operator. What will then happen if they do not get any information? The answer is that we do not know. Probably motorists do not sit in their cars until the fire is too big and surrounds them. Voeltzel´s (2002) conclusion from the fire in Mont Blanc Tunnel and the Tauern Tunnel is that people stay in their cars for as long as they do not experience the threat from the fire. Thus a possible answer is that people stay in their cars until the fire implies an immediate threat, and then it could be to late to evacuate.

Can group effects be modelled? Group effects are ignored in the modelling perspective as long as the group is treated as a number of individuals, each randomly assigned to one of the first three branches of the event tree (although minding the 9, 9 and 82% probabilities of the branches that is the result of group effects in the tests in some cases). An alternative is to assign all motorists *as a group* to one of the branches of the event tree. The assumption is that where one sheep goes, another follows. In most situations, the group will be assigned to the most likely branch (82%) - staying in the car until the call of the operator.

As said before, not much can be said about evacuation from a train tunnel because there is less data about trains. The data permit an accurate estimation of the flow of passengers through the train exits, depending strongly on the vertical distance and, to a lesser extent, on the luggage carried. There is no data on awareness time and hesitation time.

When evaluating the design of tunnels it is however of most importance to compare the total time spent in the tunnel before the evacuation is completed to the time that is considered critical, for example when the density of toxic smoke is too high or it is too hot.

Separate analyses should be made each time a tunnel is designed to determine when critical conditions appear inside the tunnel. Then this “critical time” should be compared to the total time needed for evacuation.

Some distributions end at infinity; that is, very slow. This could also happens in reality; e.g. a person who cannot walk, or get really paralysed. The probability for this is low but there are always some chances that it could occur.

7 Organisation

7.1 Introduction

When an accident in an underground space occurs we have seen that it is important to provide guidance and confirmative information to the people in the tunnel as fast as possible. This is necessary to shorten the evacuation time and to make the evacuation behaviour as efficient as possible.

The control room is the only place with total survey of the tunnel. Usually, people in the control room are responsible for making the traffic run smoothly and safe. In case of an accident their role changes depending on predetermined guidelines, sometimes involving far-reaching responsibility with vital importance for the solution of the accident, sometimes the role is limited to alerting rescue services that there has been an accident.

In this chapter different approaches are discussed and exemplified by two control rooms, the control room of the Ij- and Piet-Hein tunnel in the Netherlands, and the control room of the Öresund link between Sweden and Denmark. At first relevant literature is reviewed and discussed, then follow comparisons between the different approaches – especially the incident-specific and the universal approach.

7.2 Literature review

7.2.1 Organisation building

Vardy and Wright (1998) provide guidelines for the design of planned responses to incidents. Procedures should

- minimise opportunities for ignorance and minimise their potential to disrupt intended plans.
- minimise opportunities for errors and minimise their potential to escape detection.

The first of these implies, for example, that the need for incident-specific information should be reduced as far as possible for *everyone*. It further implies that this is especially important in the case of decisions that will have far-reaching impact.

The second guideline implies, for example, that the number of actions to be taken in a hurry should be reduced as far as possible. Rapid responses by individual operators in an emergency are inherently less fully considered than procedures devised by planners in the relatively unstressed environment of a design office.

7.2.2 Universal or incident-specific decision making

Vardy and Wright (1998) discuss the differences between incident-specific response and universal response from the control room. For the configuration of the smoke evacuation fans in the event of a fire, the difference between the approaches could be described in the following way.

The meaning of universal response is that in one tunnel control room, a mimic of the tunnel might be permanently displayed within immediate reach of the operator. In the event of fire the only action required could be to press the “red button” that is nearest to the location of the fire on the mimic board. In the incident-specific control room, on the other hand, an operator might be required to

- obtain details about a) the nature of the fire, b) its precise location, c) conditions elsewhere in the tunnel system;
- decide the most appropriate direction and speed of airflow;
- decide which fan and damper settings will achieve this demand;
- issue the necessary commands to achieve these settings;
- inform all necessary persons about the particular actions taken.

From the point of view of human fallibility the universal approach is superior to the incident-specific. In contrast, the incident-specific approach provides numerous opportunities for error and less likelihood of detecting errors.

As the incident-specific approach is uniquely designed for every situation this approach provides a higher theoretical maximum of success (100%) in an accident. However, the likelihood is lower to achieve the maximum and therefore the expected success rate also is lowered (50%). The likelihood for an optimised result becomes lower because there are more decisions to be made.

The universal approach can not be as optimised as the incident-specific in every unique situation, but because decisions that at least grant a quite good result is predetermined the result will neither bee very bad. Vardy and Wright illustrate the dilemma by the following table.

Table 7.1 Expected success rates

	Incident-specific approach	**Universal approach**
Theoritical maximum	100%	85%
Pragmatic expectation	50%	70%

“Success” above is intentionally undefined. However, the incident-specific approach gives a pragmatic expectation of, say, a 50% success rate while the theoretical maximum is 100% due to the flexibility of the approach. The universal approach results in a lower theoretical maximum but a higher pragmatic expectation because of the lower flexibility.

The human fallibility is what causes the differences of the approaches. In the totally incident-specific approach decisions have to be made for every situation that might occur during the course of the incident. Correct decisions in every situation provide the theoretical maximum but more decisions make the likelihood greater for wrong decisions in stressful situations.

Kirwan (1994) made a lot of research about human fallibility in control rooms in nuclear power plants. He means that the human error probability is as much as 0.3 when the operator should do a complicated non-routine task under stressful conditions.

7.2.3 Risk Management as a Control Problem

Risk management according to **Rasmussen & Svedung** (2000) is a control problem. They discuss the differences between systems controlled by *pre-planned strategies* and prescriptive procedures and systems controlled by *closed-loop feedback strategies.*

A pre-planned strategy means a detailed design of the system combined with detailed instructions given to the operator. To explain the difference between an open- and a closed-loop strategy, Rasmussen & Svedung compare aiming of an conventional artillery cannon to the use of an active, target seeking missile that can itself observe the location of the target. To plan a shot it is only necessary to specify the target (the objective) to the missile that then "locks on" to it. In addition to *specifying the target*, the planner/designer needs only information about *the capability* of the system. Information about changes and disturbances are not needed, as long as the closed loop control system is within its capability design envelope.

Closed-loop feedback is necessary when the system to be controlled is subject to unpredictable disturbances. Feedback control is based on a comparison of the observed state of the controlled system with a reference value. The control action will then serve to minimize the deviation between the observation – a measurement – and a reference value (Rasmussen & Svedung, 2000).

7.2.4 Information

In the report by **Proulx and Sime** (1991) the importance of early and appropriate information is underlined. Five different experiments were performed in the Tune and Wear Metro. In the tests information was given in different ways, see chapter 1 for more details. The conclusions were that an active guiding from the control room via the PA system resulted in the most appropriate evacuation behaviour. An overview of the situation was given to the control room by the CCTV-system. This role of the control room demands that the staffs can interpret the information given on the CCTV-system and make several correct incident specific decisions, for example guide single persons to the right exit. They should also give information to the rescue personal and the tunnel staff.

7.2.5 Everyday reaction compared to action during accidents

Reason (1997) discusses research in military groups where a daily supervising role is changed to a sudden attack role when the enemy is in range. He concludes that organisations with high internal reliability are able to shift from centralised control to a decentralised mode in which the guidance of local operations depends largely upon professionalism of first-line supervisors.

Paradoxically perhaps, the success of this transformation depends on the prior establishment of a strong and disciplined hierarchical culture. It is shared values and assumptions created by this culture that permit the coordination of decentralised work groups. Effective teams, capable of operating autonomously when the circumstances demand it, need high-quality leaders. This, in turn, requires that the organisation invest heavily in the quality, motivation and experience of its first-line supervisors.

In systems that include trial-and-error learning, maintaining reliability depend on developing alternatives for trial-and-error. This could include imagination, vicarious experience, simulation, stories and storytelling. A system that values stories and storytelling is potentially more reliable because people know more about their system, know more of the potential errors that might occur, and they are more confident that they can handle those errors that do occur because they know that other people have already handled similar errors.

7.3 Management systems

From the literature review and the earlier chapters of this report it is concluded that the control room should provide guidance and information to the people in the tunnel as fast as possible. It is important that the design of the organisation minimise the risk for human errors and if they still occur the consequences should be minimised. The decisions made by the control room should be both the best decisions possible in the specific situation and made as fast as possible. It is obvious that not all the desirable features can be achieved simultaneously; still the result in total should be optimised.

The classical approaches in decision-making theory may be defined as *deontological ethics* and *situational ethics*. Deontological ethics assume that it we should apply absolute principles or rules in every situation to achieve the best result in general. Situational ethics on the other hand believes that the best result in each case is achieved regardless of absolute principles or rules because clear-shared values should define the goals of our actions.

The incident-specific approach in decision-making corresponds to the background of situational ethics and the universal approach corresponds to the deontological. Which approach that optimise the result in control rooms is impossible to state, but the two examples of the control rooms in the IJ and Piet-Hein tunnel and Öresund link will represent one ethical background each, to se which the consequences are.

7.4 Visited tunnels

7.4.1 Ij-and Piet-Hein tunnels

The tunnels

The IJ-tunnel opened in 1968 and was constructed in the late fifties. The tunnel is 1129 m long and goes under the river Ij in Amsterdam, Netherlands.

The Piet-Hein tunnel opened in 1997 and is 1492 m long. The tunnel goes under the Rhein Canal in Amsterdam.

The two tunnels have a common control room located over the Piet-Hein tunnel.

Both tunnels are two-tube tunnels with a service and escape line between the tunnel tubes. There are emergency doors between the tunnels and the escape line. Normally they are locked to prevent unauthorized personal to get in. The doors can be unlocked from the control room and it is one of the tasks for the staff during an evacuation.

Staff

Three persons are in duty in the control room daily. In nights and in weekends there are two persons in the control room. They work in 8 hours shift, 36 hour/week. A new operator gets 6 month in-service training, before he is allowed to work alone.

Daily work

The three persons in duty have alternating tasks during the day. Two persons sit in the control room and supervise the CCTV in the tunnels. One person checks the IJ-tunnel and the other one person checks the Piet-Hein tunnel. The last person is a mobile resource, who goes round in the tunnels if something would happen. In the nights and in weekends are there two persons who supervise the CCTV and if something would happen one of them goes to the tunnel and the other then have to supervise two tunnels. Every hour they shift tasks.

The operators have authority to stop the motorists and give them tickets if they wont follows the traffic rules. They used to be in the police organisation but now they in the Amsterdam road organisation.

The control room is shown in the figure below.

Figure 7.1 The control room of the Ij tunnel

Organisation at accidents

The first thing to do is to call the fire brigade and the police. There is a direct phone to the regional alarm centre, but the operator has to tell all about the accident. This takes a few minutes.

In case of an accident the tunnel staff members assist the fire brigade. One operator goes to the accident site and the others stay in the control room. The communication between the incident commander and the control room goes via the tunnel staff member at the accident site.

The control room operator makes the decision to evacuate the tunnel as well as to start to force the ventilation. There is often no conversation between the incident commander and the operator before the operator starts to act. There are neither any instructions for the operator to support the decision-making. The operator has to improvise; the policy is that every accident is unique and therefore no checklist that suites all accidents can be designed. As long as the operator knows about the tools available he will make the best possible decisions about how to use them in any specific situation.

Tasks during accidents

The tasks for the operator(s) during a fire in the tunnel may be to:

- Stop the traffic. Press one button
- Collect emergency calls from the tunnel
- Call the fire brigade and the police
- Unlock the emergency exits
- Evacuate the tunnel via the PA-system. The operator has to think about what to say.
- Guide the fire brigade to a proper location.
- Guide the colleague in the tunnel to a proper location
- Start the ventilation. It takes about three minutes to warm up the diesel engines.
- Keep an eye at the other tunnel.

7.4.2 Øresund Link

The link

The Øresund fixed link is a 16 km road and rail link, which comprises three main elements: a bridge, an artificial island and a tunnel. The tunnel is approximately 4 km long.

Since the link connects the two countries Denmark and Sweden special problems associated with the meeting of different technical systems, different organizational traditions and different cultures arise. To minimise the risk for misunderstandings extra attention has been paid on such differences. The link was inaugurated on July 1, 2000.

Staff

The people that work in the Øresund link control room work together in teams consisting of two persons. Most of the staff has experience from working as 112 operators, coordinating different public agencies such as police and fire resources.

Daily work

The every-day work in the control room consists of supervising the link via CCTV monitors and other technical installation that provide information about the status of the motorway traffic (see figure7.2). If the weather conditions are too bad the members of the staff close the tunnel for example. The staff members in the control are also responsible for the employees in the nearly located toll station.

Figure 7.2 The control panel of the Øresund link

Organisation in case of accident

All incidents on the bridge or in the tunnel are classified under one of three categories: Level 1 indicates the smallest level of accident or incident; Level 2 and 3 indicate normal or more intensified resource requirement.

The staffs in the control room are responsible for classifying each incident depending on the type of incident. When a vehicle comes to a halt inside the tunnel (or drive slower than a certain speed limit) the CCTV system automatically detects the vehicle and a monitor inside the control room show the vehicle. To alert the staff there is a sound alarm in the control room. If the staffs consider the incident a level 1, 2 or 3-accident they fill in a computer-based form with information about the location of the accident, number of cars involved et cetera. When they press the “send” button the form is sent automatically to pre-determined recipients, e.g. the police and fire resources.

Except for the control room both the Swedish and Danish police and fire departments can follow the CCTV cameras via monitors.

As soon as the message about the accident is sent the decision-making responsibility lies on the incident commander, if the location of the accident is in the tunnel the incident commander will come from the Danish police. The incident commander makes all decisions about necessary reinforcements or other needs, and also decides about how to use the fans if there is smoke in the tunnel, even if these fans are manoeuvred from the control room.

If there is a level 2 or 3-accident an additional staff member arrives from the Swedish fire department to help coordinating the different resources.

Tasks during accidents

As mentioned above, once the incident is classified the staff members in the control room have limited responsibility. The staff members are responsible for

- evacuating vehicles from the tunnel (they can broadcast directly on the FM-channels in the tunnel)
- keeping the lanes free
- if the ventilation system does not start automatically, the staff members can start it

7.5 Evaluating the systems

Of the two control room examples the Ij- and Piet-Hein tunnel control room is a good example of the incident-specific approach. The Öresund link control room on the other hand, is a good example of the universal approach.

It is obvious that while most decisions in the Ij- and Piet-Hein tunnel control room demand creative solutions, the corresponding situations in the Öresund link control room are supposed to be foreseen and the decisions predetermined. Referring to the matrix describing expected success rates (Table 7.1) a higher theoretical maximum is expected in the Ij- and Piet-Hein tunnel control room since the decisions are more flexible. However this implies that “success” only is a matter of which decisions are taken and how well they are accomplished. In an emergency not only the appropriateness of the decisions matters but also the times until decisions are made. As we have seen in the earlier chapters of this report, it is of great importance to give confirmative information as early as possible to help people make the decision to evacuate. This is another way of discussing success, as the time to make decisions. There is no doubt about the fact that the Öresund link control room, representing the universal approach, is the faster one of the two approaches when it comes to decision making.

To make the control room work well different things are necessary in the two approaches. In the Ij- and Piet-Hein tunnel control room it is necessary that the staff

- are capable to make creative decisions under stress
- are trained to work efficiently in stressful situations
- are well aware of how systems work in order to make the most appropriate decisions
- know each other well, i.e. are aware of the qualities and shortages of the other staff members in the control room and
- know how to make the group of staff members work as a team

In the Öresund link control room it is important that

- there are very well-planned routines covering all possible scenarios
- that all routines are well known and followed not only by the staff in the control room but also by police and fire squads even if there seems to be better ways to handle the situation
- that the systems that the work in the control depend on never fail

No matter what approach is studied, there will never be a "perfect" system depending on the fact that people as well as the world around change and accidents that could not be anticipated at one time becomes possible later. Therefore, after incidents it is important to learn from mistakes and to find ways to improve the work. This is as important in the incident-specific approach as in the universal approach.

Organisations working with risk management in a proactive way are capable of identifying rooms for improvement even without occurring accidents. This is what every control room must be able to do.

In the universal approach it is important to discover situations that are not covered by existing routines. This is hard to discover by regular training exercises, since the goal of such drill exercises in general is to make the operator work faster and more efficient. Also, to train for situations that never seem to occur soon leads to absurd exercises, with questionable actuality for the trained staff members. What is needed is to train the ability to recognise situations that are not covered by routines and to learn how to act in such situations.

In the incident-specific approach it is necessary to train the ability to see mistakes and to use the sum of the capacity of the group. This means that an atmosphere that allows misinterpreted situations to be discovered must be created and maintained. Critical remarks from subordinated staff members about decisions made by superior staff members must be paid attention, something that usually is a matter of prestige and demands long-term work with group-process and feed-back training.

7.6 Discussion

Perhaps most control room staff members are not aware of the background of the system that they work with daily. What is most important in the daily work is of course to follow the rules and guidelines of the current system, whether it is the incident-specific or the universal approach that forms the background.

It is though important for all people involved in the control room work to sometimes pay attention to the art of the system in order to realise what kind of mistakes that can be expected and which the shortages are. Only if the staff members regularly question the system and try to discover where shortages can occur, the system can be developed and optimised.

7.7 Conclusions

The tunnel control rooms of the Ij- and Piet Hein-tunnel and the Öresund link tunnel represent two different approaches – the incident-specific approach in the Ij- and Piet Hein-tunnel control room and the universal approach in the Öresund link control room.

The incident-specific approach allows a higher theoretical success maximum since it is more flexible and allows more creative solutions while the universal approach is supposed to result in faster decisions with lower flexibility.

The incident-specific approach in decision-making corresponds to the background of situational ethics and the universal approach corresponds to the deontological. It is not possible to state which approach to prefer when designing control room systems, only that it is important to be aware of the benefits and the shortages of the different approaches.

8 GENERAL DISCUSSION

The results of this study are based on experiments performed in several train tunnels and one road tunnel, the Benelux tunnel in the Netherlands. These experiments, together with knowledge achieved from earlier reports discussed in the literature review are what have resulted in the conclusions. It is though necessary to keep in mind that the results and conclusions presented in this report are valid only for similar objects and under similar circumstances as the tunnels discussed in this report.

In the study of the evacuation time conclusions are made about the dependence of different factors on the duration of the evacuation. Even if several different factors such as the position of the cars in the tunnel (relative to the accident and relative to the emergency exits), the presence of other people, the slope in the tunnel and the announcements were considered, there will always be more factors remaining that affect the evacuation process in ways that can not be fully surveyed. However, of most importance is that the dependence of factors that can be controlled is known and quantified, in order to make it possible to plan for the consequences of such factors. There is simply no possibility to know in advance exactly all the parameters that will appear when an accident occurs inside a tunnel, and therefore it is most relevant to study the factors that are believed to be crucial in a general perspective.

The approach of the quantified three-stage model used in this report could be questioned - perhaps it is wiser to see the course of events during an evacuation as one action, not distinguishing stages in the process from one another? Using that perspective, however, there is no understanding for the different factors that undoubtedly affect the human behaviour in different extent. Even if the total evacuation time would be similar and achieved with less effort, it would be impossible to know how to shorten the evacuation time, i.e. which factors that are most important.

Another benefit of the three-stage model is that it brings about a possibility to study the stages separately. If, for example, anyone would be interested in comparing the walking speed study in this report to real scenarios or other studies, this would not be a problem.

What is most important is to understand the factors that shorten the evacuation time. In this perspective it is clear that the organisation of the work in the control room plays an important role. It is necessary to design the organisation in a proactive way according to the actual needs of the system and to be aware of the shortages of every system, shortages, i.e. room for improvement resulting in safer tunnels.

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Appendix

CONTENTS

APPENDIX A – ROAD TUNNEL TEST

The purpose of this appendix is to provide detailed information about the nine tests. First a short description of the test method is made. This is followed by the analysis plan for the video analysis.

Each of the nine tests is described in detail with information about the number of participants and any remarkable or significant behaviour. A summary of the information is presented in a table in the end of every test description. The reaction of the motorists is also shown in a graph for each test.

The data of the tests are then analysed and a distribution is calculated for each step in the evacuation. The three steps are “Leaving the car”, “Hesitation time outside the car”, and “Walking time”.

A.1 Description of the evacuation test

Data for the road tunnel evacuation tests were collected in the Benelux tunnel in Rotterdam in the Netherlands. Below follows a description of how the tests were carried out as well as a description of how the information has been analysed.

The Benelux tunnel is more than 1 km long and consists of five different tubes. The study took place in tube D. This tube is almost 10 m wide with driving lanes of 3.5 m width and an escape strip of 1.5 m next to either wall.

In the tunnel there are 12 emergency exits, painted with numbers from 1 to 12. The internal distance between two exits is 100 m except for the distance between exit 6 and 7, which is 50 m. The deepest point of the tunnel is between exit 6 and 7 (25 m below Amsterdam Ordnance Datum, reference level the Netherlands).

All exits consist of sliding doors on the right hand wall. When passing through the emergency exits people come to an evacuation tube which is used for both tube D and E. Between Exit 6 and Exit 7 in the evacuation tube a pump installation blocks the tube, making it possible to evacuate in southerly direction from Exits 1 to 6 or in northerly direction from Exits 7 to 12. The driving direction is from the south to the north.

Above the emergency exits, at a height of more than 4 m, dual emergency signboards have been fitted, showing from the left to the right a door, an arrow and a small running person. The symbols are printed bold and illuminated. The door itself is marked with the number of the door and the tube, e.g. *6 D*. There are no escape route signs on the doors.

In the tests a Heavy Goods Vehicle (HGV) followed by cars in both driving lanes entered a one-way tunnel with two driving lanes. In the middle of the tunnel smoke started to develop from the truck. The truck slowed down and stopped, blocking both driving lanes.

Approximately five minutes after the truck stopped an announcement was made via the loudspeakers in the tunnel, saying "Attention, attention, there is an explosion hazard; I repeat, there is an explosion hazard". The duration of this announcement was about five seconds. It was made twice, so that the total duration was 10 s.

After two more minutes, i.e. seven minutes after the HGV stopped, another announcement was made saying, "Please leave the tunnel [via the emergency exit doors]; please leave the tunnel [via the emergency exit doors]". The longer version (A) was used in Tests 2, 3, 5 and 6 while the shorter version (B) was used in Tests 1, 4 and 7. This second announcement in the tunnel was also made twice. The total duration of Version A was approximately 10 s and Version B 15 s. Version A was then repeated every 50 s and Version B every 30 s.

In total nine tests were made. Two of them were control tests (Test 8 and 9); in these the participants were told before the test that they should evacuate as soon as the HGV comes to a halt. In the other seven tests the participants had been informed in advance that the purpose of the test was to study driving behaviour, although this specific time they were told that they were only driving through the tunnel to get familiar with it and the study itself would take place later. Therefore they did not expect that an evacuation could take place.

In each test four cameras recorded in the tunnel. The camera view is from the HGV and 140 meters back, i.e. between Exit 6 and 8.

The purpose of the video analyses is to determine the time it took from the moment that “the accident” happened until people started to act. Also, the walking speed in the tunnel and the time to leave the tunnel is to be estimated. This is to be compared to the time when the HGV stopped and when the different announcements were made. Before people decided to evacuate and started walking towards the exits there may be some time spent watching in fascination, thinking et cetera. This hesitation time is to be estimated when possible.

About 50 drivers participated in each test. Directly after the truck in every test a person from TNO were driving, to make sure that both driving lanes were blocked and making it impossible to overtake the HGV. At the end of the row of cars there were also TNO staff, with the task to make it impossible to reverse or drive out of the tunnel in the wrong direction once the traffic jam was a fact. The participants in the test did not know about this, they believed all drivers were just ordinary people. The TNO employees are not considered in the analysis.

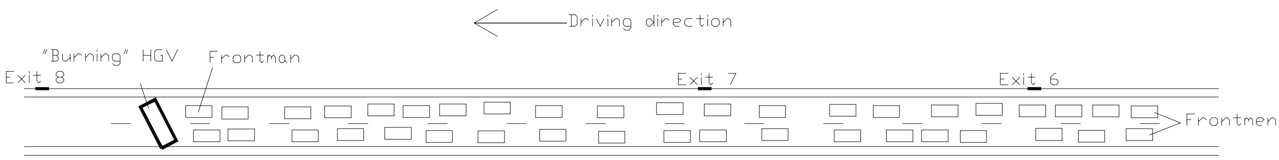
The participants were told to come by car alone, i.e. only one person in every car. Still, two persons in the same car were observed six times. In Tests 2 and 7, two cars had two people each; in Test 3 and 4 one car carried two individuals. In these situations only the driver’s behaviour has been analysed. These minor violations of the instructions should not have affected the results.

Since the queues were longer than expected and not totally covered by the cameras in most of the tests only about 30-35 cars could be analysed in most of the tests. In total the behaviour of 193 drivers was analysed.

A survey was made among drivers using the tunnel to be able to see how familiar to the tunnel the participants of the tests are in comparison to ordinary users. The experience of the participants in the test was as follows:

- 37% uses the tunnel daily or more often (Survey: 53%)
- 33% uses the tunnel (Survey: 30%)
- 12% uses the tunnel approximately once a week (Survey: 12%)
- 19% uses the tunnel less than once a week (Survey: 5%)

The conclusion is that the participants have slightly less experience from driving through road tunnels than the average motorist who happens to drive through a road tunnel.
Figure A1 Test settings.



A.2 Analysis plan

To be able to repeat the analyses and achieve the same result, which is the main character of a scientific study, the way that the analysis is carried out must be specified. In this case the analysis has been carried out with the following rules and definitions:

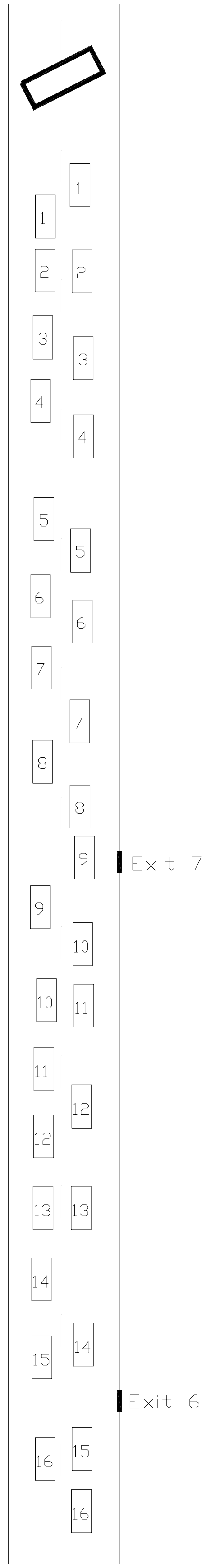
- The start time for the accident (t_0) is when the HGV stops. (When comparing different results however, t = 0 is set when the announcement is made and the time when the HGV stops is counted negative on the timescale.)
- The cars are counted one by one and they are numbered from the HGV in each driving lane, e.g. L1, L2, L3, …., Ln and R1, R2, R3, …., Rn.
- Only those cars where it is possible to study the driver when he opens the car door are counted.
- The time to act for each driver is said to be when he puts his foot on the ground.
- The time when the person passes through the emergency exits is noted for each driver.
- The hesitation time is from the moment the driver puts his foot on the ground for the first time until he/she starts walking towards an emergency exit.
- Only those persons that can be followed from the car to the emergency exits are considered.
- The time when the different announcements are made is noted. (I.e. the starting time for the announcements).
- Notes are made about people acting in a way that is not logic due to the rules above, e.g. persons who get back to their cars after having disembarked.
- If there are two or more persons in the car, only the driver is considered.
- The distance to the emergency exit is the sum of the perpendicular distances from the front door to the emergency exit.
- Each car is said to be four meters long and 1.8 meters wide.
- For each test a map showing the position of each car is made. From this map it is possible to calculate the distances.
- The walking speed is calculated as the perpendicular distance from the front door of each car to the chosen exit divided by the walking time measured from the moment that the driver starts to walk towards the exit until he/she passes it.

A.3 Test 1

A.3.1 Description of the tests

Test 1 took place on the 8th of January at 19:15.

In the test 32 cars were viewable for the cameras. Excluding the frontman (R1), this results in 31 cars to analyse. The position for each car is shown in figure A2 to the right.



The first announcement, “explosion hazard”, was made 280 seconds after the HGV stopped. The second announcement, “leave the tunnel”; was made after 400 seconds.

A.3.2 Results

The first person stepped out from his car after 175 seconds. This was the person, L1, who drove just behind the truck. The rest of the people started to act after the first announcement sounded at 280 seconds. The last person left his car after 365 seconds. The first person that did exit the tunnel was R15 after 349 seconds, 69 seconds after the announcement. The last person reached the exit 51 seconds later at 400 seconds. This means that the time until the last person exit the tunnel is 120 seconds after the announcement.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A3 below. The complete test record follows on next pages.

L1 left the car after almost 3 minutes, walked to R1 (the frontman) and started talking with him. After one minute he returned to his car. He was the only person who left the car before the announcement. All the others sat tight in their cars and waited for the road to be clear. From the way that the drivers behave in this test it is evident that they need a confirmation that they are in danger and that they have to evacuate. The smoke from the truck was not enough to provide a confirmation. The people did not feel any treat from the smoke. Although when the announcement was made they started to evacuate quite fast.

In the test the mean hesitation time was 24 seconds. If L1 is not counted the mean hesitation time was 20 seconds. Most of the hesitation time was spent discussing with other motorists. 3 motorists returned to their cars, turned them off and locked them.

The walking speed was above the total average; see Chapter 3. The mean walking speed was 1.5 m/s, which is to be compared to 1.37 m/s.

Only one person reacted before the announcement although the traffic stood still for almost five minutes and smoke filled the tunnel.

The second announcement that the people should leave the tunnel does not matter for the result of the test since every person had left the tunnel when this announcement was made.

In the left lane the motorist chose the closest way to the emergency exits. L12 walked to Exit 7 and L13 walked to Exit 6. In the right lane R11 went to Exit 6, which is 41 m away, although the distance to Exit 7 was only 18 m.

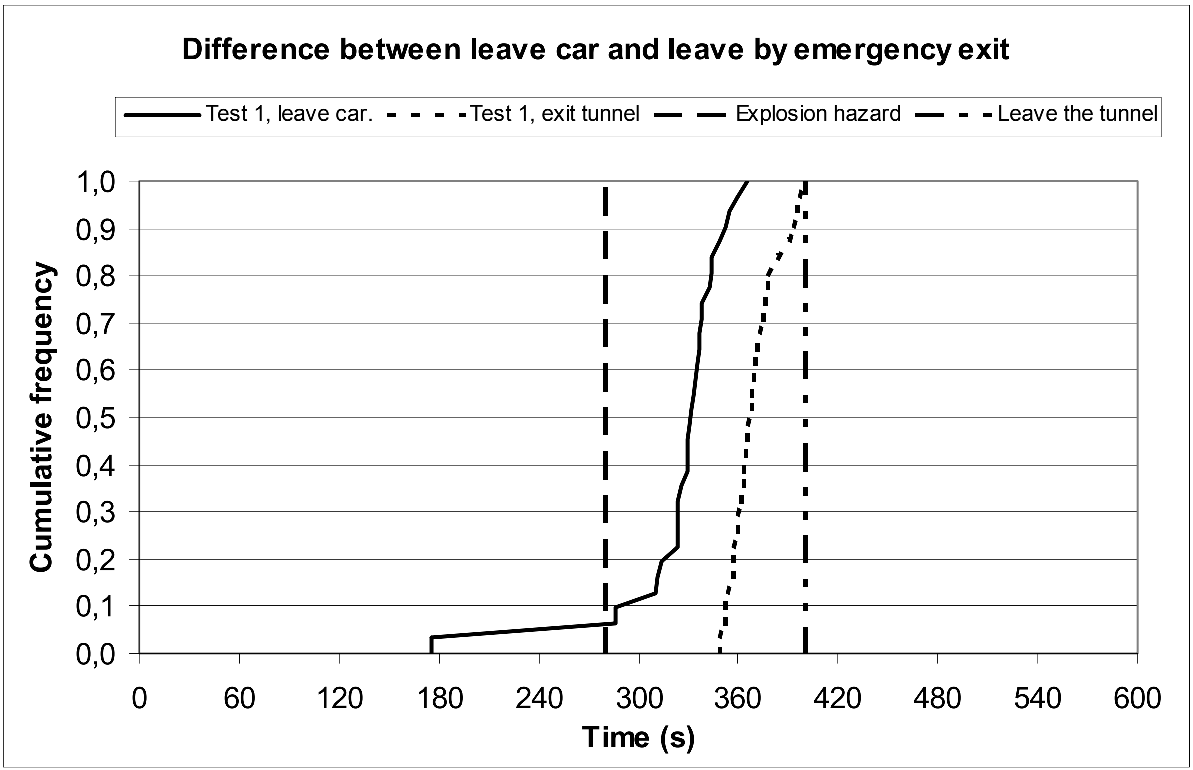


Figure A3 Motorists leaving the car and motorists leaving the tunnel.

Table A1	Test 1 (8 Jan)	
	Announcement: "explosion hazard"	**280 sec**
	Announcement: "leave the tunnel"	**400 sec**
	Counter starts (t0) 19:15:09	

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
L1	175	372	167	68	2,3	Talks with FM. Back at car at 233 s.
L2	312	375	0	63	1,0	Talks with L3and L4.
L3	314	369	0	56	1,0	Talks with L2 and L4.
L4	334	373	0	50	1,3	Talks with L2 and L3.
L5	326	359	25	17	2,1	Walks outside camera range. Walks from L8.
L6	324	357	20	32	2,5	Walks around, uncertain of the direction.
L7	338	363	15	25	2,5	Goes back and close and lock car.
L8	359	400	30	17	1,5	-
L9	333	395	52	12	1,2	Walks away and returns to car.
L10	324	363	30	21	2,3	Locks car, discusses with L11.
L11	323	376	35	27	1,5	Locks car, discusses with L10.
L12	365	383	5	33	2,5	Uses exit 7.
L13	355	378	4	25	1,3	Uses exit 6.
L14	349	370	0	19	0,9	-
L15	336	352	7	12	1,3	Discusses with L16.
L16	338	368	20	14	1,4	Discusses with L15, turns off car.

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
R1	Frontman (not counted)					
R2	286	397	81	59	2,0	Turns off and locks the car, walks around.
R3	344	393	29	51	2,6	Turns off and locks the car.
R4	344	391	20	44	1,6	-
R5	329	362	8	33	1,3	Locks the car.
R6	331	352	8	26	2,0	-
R7	330	357	20	17	2,4	Walks around car L6.
R8	337	354	5	9	0,8	-
R9	286	368	72	6	0,6	Walks around and goes back to his car.
R10	329	365	18	12	0,7	Turns off and locks car. Uses exit 7.
R11	337	378	19	41	1,9	Turns off and locks car. Uses exit 6.
R12	310	357	22	31	1,2	Locks car.
R13	343	364	4	21	1,2	-
R14	352	366	5	9	1,0	-
R15	323	349	15	9	0,8	Short discussion with car behind.
R16	332	359	17	15	1,5	Short discussion with car in front.

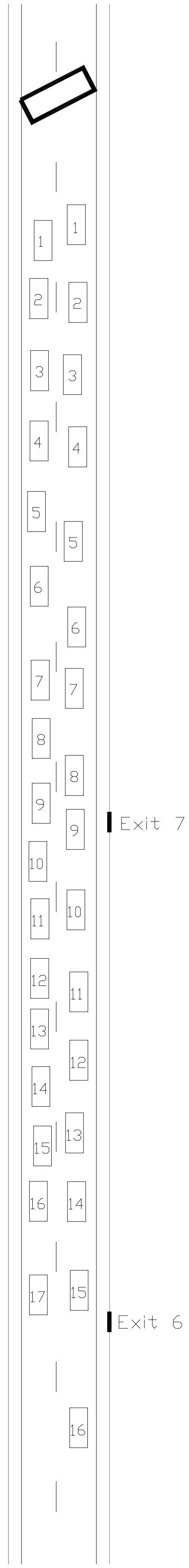
Sum	10118	11465	753	874	48,3
Mean	326	370	24	28	1,6
Std	32,7	13,8	32,3	17,4	0,60

A.4 Test 2

A.4.1 Description of the test

Test 2 took place on the 8th of January at 20:45.

In the test 33 cars were partly viewable for the cameras. One of them was the frontman and is therefore not analysed. Thus the analysis is based on 32 cars. The position for each car is shown in figure A4 to the right.



The first announcement, “explosion hazard”, was made 300 seconds after the HGV stopped. The second announcement, “leave the tunnel”, was made after 390 seconds.

Two cars in this test contained two persons, a passenger except for the driver. Only the behaviour of the drivers has been analysed.

A.4.2 Results

In this test a spontaneous action started quite fast, shortly after the HGV stopped. A few drivers also decided to evacuate at this early stage whereas most of the drivers hesitated for several minutes, discussing with other drivers.

The first driver leaving his car is R6 who left his car 14 seconds after the HGV came to a halt. This driver’s early reaction was followed by the reaction of about 10 other drivers in the vicinity. In total 16 drivers left their cars within a minute after the HGV stopped.

A few drivers also left the tunnel at an early stage; R6 was the first one to get out after 38 s. However, most of the drivers that reacted fast then hesitated for a long time, deciding to evacuate only after they heard the announcement. They spent the hesitation time investigating the fire extinguishing equipment, using the emergency phone, discussing with other drivers and similar, what is to be typical orientation behaviour.

For those who had not reacted within 200 s the announcement made at 300 s was what made them react. This announcement made all participants that were still in the tunnel start evacuating. The last one left the tunnel at 368 s.

The mean hesitation time in the test was 115 s, which is the longest time of the different tests. It is evident that although many drivers react fast they had not decided to evacuate when they left their cars.

The walking speed was close to the average speed; 1.4 m/s in the test compared to the total average of 1.37 m/s. (see Chapter 3).

In this test the danger the situation itself provided was enough to make many of the participants react and leave their cars. Still, only a few decided to evacuate and many drivers tried to solve the situation. It is hard say whether those that stayed in the tunnel made the decision at an early stage to first try to solve the situation, e.g. by phoning via the emergency phone, and evacuate after this, or whether they are simply searching for information. It is though easier to state that once they heard the announcement, the people in the tunnel decided to evacuate no matter which their earlier decisions were.

Only one driver, R13, chose to walk to an exit that was not the closest one, Exit 7 instead of 6.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A5 below. The complete test record follows on next page.

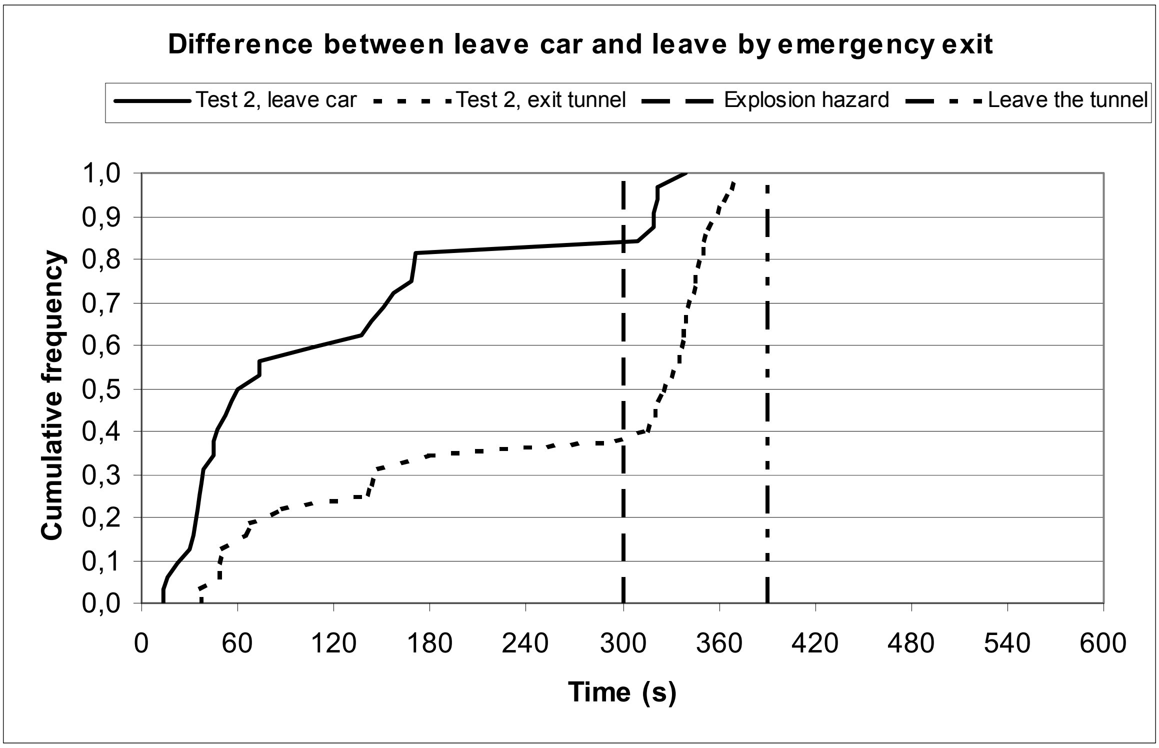


Figure A5 Motorists leaving the car and motorists leaving the tunnel.

Table A2 Test 2 (8 Jan)

Announcement: "explosion hazard" 300 s
Announcement: "leave the tunnel" 390 s
Counter starts (t0) 20:43:58

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed	Other
L1	74	326	239	22	1,7	Turns off the car, joins the discussion group close to the phone. Walks from L7.
L2	47	368	299	60	2,7	Talks to other people standing close the emergency phone. Goes back to the car and turns it off and then walks back to the discussion group. Walking around and at least starts to walk slowly to the exit. When he almost has reached the exit he returns to t
L3	16	51	5	53	1,8	Two in car.
L4	32	141	94	23	1,5	Two in car, the passanger evacuates ímmediately after the car stops, running. The driver talks to other people and walks around. Walks from R6.
L5	30	143	89	38	1,6	Walks directly to emergency phone and pick it up.
L6	39	89	28	31	1,4	Talks to L5 and L4. Returns to his car at 90 s, turns it off and locks it. Start walk to the exit 122 s, from R6. Is out at 145 s.
L7	37	69	8	22	0,9	-
L8	45	320	264	16	1,5	Walks around close to car
L9	319	347	9	11	0,6	Locks his car.
L10	322	351	5	12	0,5	Locks his car.
L11	151	338	177	18	1,8	Locks his car.
L12	56	148	74	24	1,3	-
L13	137	345	188	29	1,5	Walks around and talk to people, returns to his car and locks he car. Uses exit 7. After 334 s he runs back to his car and pick up something and then runs back to the exit.
L14	309	339	7	31	1,3	Locks his car. Uses exit 6.
L15	143	336	183	25	2,5	-
L16	157	331	164	20	2,0	Turns off the car.
L17	74	316	233	10	1,1	Locks his car, Stands outside the emergency exit and then returns to the car. Walks from the right side of the car.

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed	Other
R1	Frontman (not counted)					
R2	23	322	275	56	2,3	Discusses with L5, L6 and some other drivers. Inventories the aid post and uses the emergency phone. Then returns to own car and locks it. Then starts to evacuate.
R3	45	297	204	49	1,0	Discusses with several other drivers before returning to own car, locking it and then starts to walk to the exit.
R4	60	373	276	41	1,1	Discusses with L5 and L6, invents equipment for putting out fire, then finally returning to car, locks car and evacuates.
R5	322	363	11	32	1,1	Locks car.
R6	14	38	7	23	1,4	-
R7	339	351	4	17	2,1	-
R8	319	340	10	9	0,8	-
R9	36	49	0	6	0,5	-
R10	170	337	154	13	1,0	Walks to R8 and talks with him, then returns to the car and sits in it and then locks car.
R11	169	359	169	21	1,0	Hanging on the car door, then turns off and locks her car.
R12	171	344	153	28	1,4	Hanging on the car door, then turns off and locks her car.
R13	35	65	0	35	1,2	Uses exit 7. Waves to the other people and try to get them out.
R14	52	180	114	16	1,1	Stands in the car door looking forward. Uses exit 6.
R15	107	353	241	7	1,4	Sits in car until she starts to evacuate
R16	34	49	0	15	1,0	-

Sum	3884	8178	3684	813	44,1
Mean	121	256	115	25	1,4
Std	107,6	121,9	102,6	14,1	0,53

A.5 Test 3

A.5.1 Description of the test

Test 3 took place on the 9th of January at 19:20.

In the test 27 cars were viewable for the cameras. Excluding the frontman, R1, this means that 26 cars were analysed. The position for each car is shown in Figure A6 to the right.

The first announcement, "explosion hazard", was made 345 seconds after the HGV stopped. The second announcement, "leave the tunnel", was made after 465 seconds.

A.5.2 Results

The first person (L8) got out from his car after 177 seconds. About 25 s later another person (L5) left his car followed by yet another person 60 s later. These drivers started discussing with other drivers and then returned to their cars.

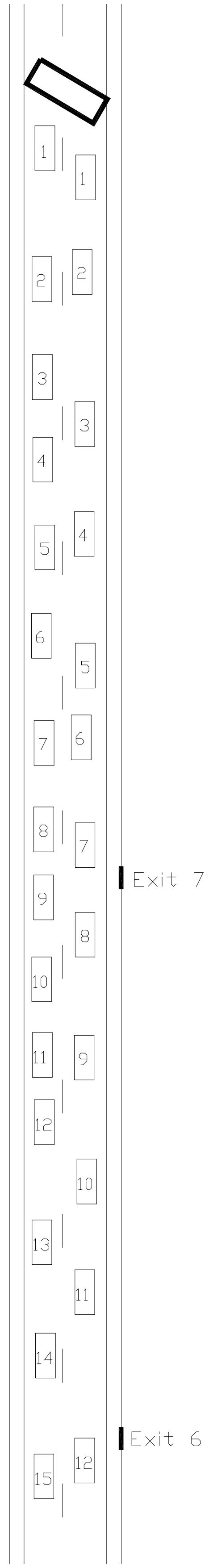
The first announcement message started up the evacuation. The first person passes the emergency exit after 367 s, 22 s after the announcement. The evacuation ran smoothly but was slower after a while. The last person was safe after 609 s.

The "leave tunnel" announcement was made after 465 s. When the last persons left the tunnel it had been made four times. Before exiting through the door some persons were standing close to the door watching what happened in the tunnel.

The mean hesitation time in the test was 36 seconds. Most of the hesitation time was spent discussing with other motorists and on orientation behaviour.

The walking speed was lower than the total average; see Chapter 3. The mean walking speed was 1.1 m/s compared to 1.37 m/s.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A7 below. The complete test record follows on next page.



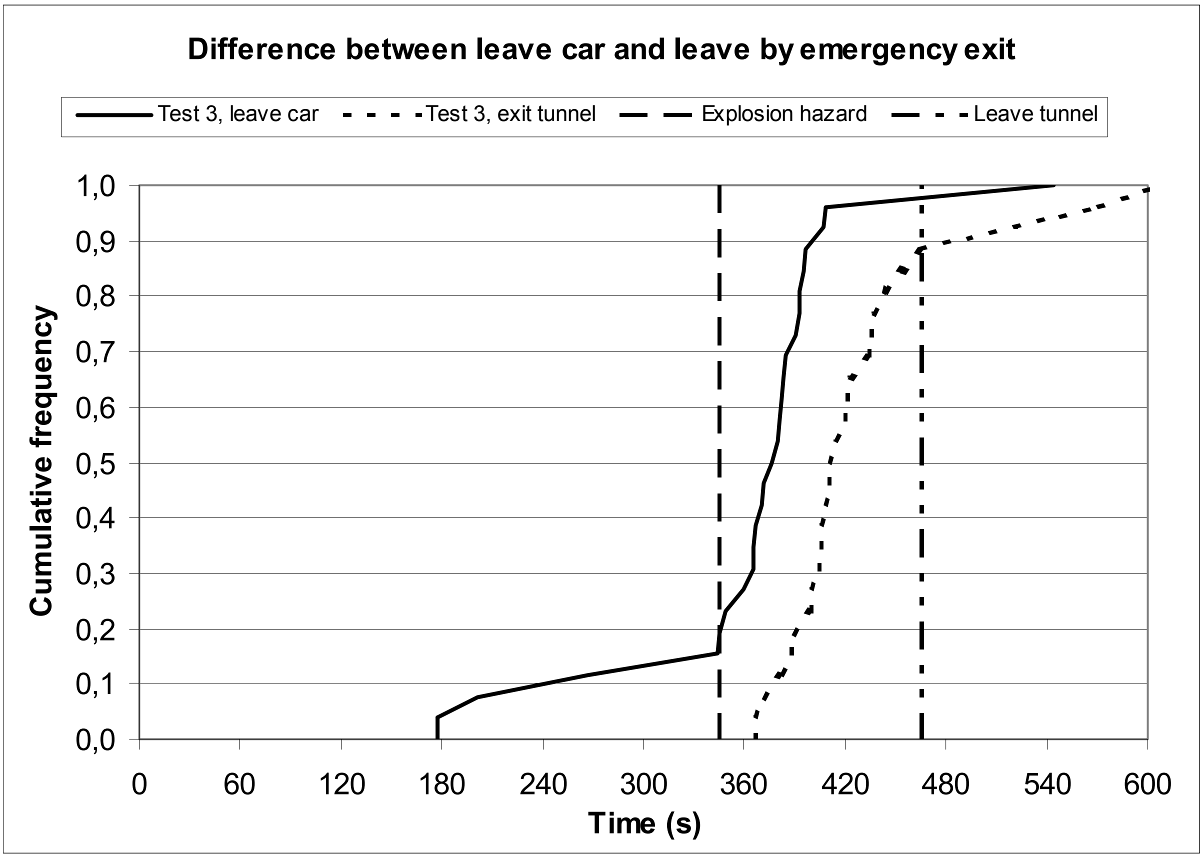


Figure A7 Motorists leaving the car and motorists leaving the tunnel.

Table A3 Test 3 (9 Jan)

Announcement: "explosion hazard" 345 sec

Announcement: "leave the tunnel" 465 sec

Counter starts (t0) 19:19:40

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
L1	544	609	10	72	1,3	Two in the car.
L2	370	571	161	62	1,6	Checks the truck untill at 480 s. Walks against the em. exit but returns to the car for his jacket at 531 s.
L3	383	453	15	52	0,9	Talks with L4 on the way to the exit. Stands in the door for 9 s.
L4	366	444	31	45	1,0	Walk back and turn off and lock the car.
L5	201	420	143	29	0,4	Gets out from the car and talks with L4 and then returns at 245 s. Walks from L6.
L6	393	421	0	29	1,0	Talks with L5 before leaving car.
L7	344	388	28	20	1,3	Stands outside car.
L8	177	367	177	12	0,9	Gets out from the car and talk with R6 and then returns at 347 s.
L9	349	371	11	10	0,9	-
L10	360	389	20	17	1,9	Walks 5 meters than hesitate.
L11	372	406	8	24	0,9	-
L12	345	414	48	31	1,5	-
L13	381	411	4	41	1,6	-
L14	407	466	3	51	0,9	Uses exit 7.
L15	395	436	31	6	0,6	Only 6 m away from exit 6 when finally deciding.

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
R1	Frontman (not counted)			66		
R2	396	522	60	58	0,9	Walks around, checks the accident. Stands in the emergency door for 26 s.
R3	385	435	21	44	1,5	-
R4	380	411	0	34	1,1	-
R5	376	406	0	22	0,7	-
R6	365	382	0	17	1,0	-
R7	367	400	21	7	0,6	-
R8	391	405	0	10	0,7	-
R9	382	423	8	20	0,6	-
R10	408	437	8	32	1,5	Uses exit 7.
R11	267	400	122	18	1,6	Talks to L12, L13, locks car, uses exit 6.
R12	393	408	7	6	0,8	-

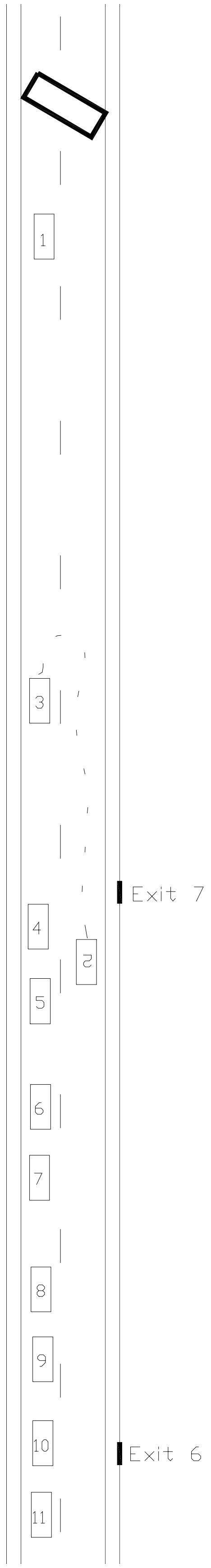
Sum	9497	11195	937	769	27,7
Mean	365	431	36	30	1,1
Std	66,3	55,8	51,7	18,2	0,38

A.6 Test 4

A.6.1 Description of the test

Test 4 took place on the 9th of January at 20:48.

In the test 11 cars were viewable for the cameras. Excluding the frontman, L1, this means that 10 cars were analysed. The position for each car is shown in Figure A8 to the right.



The first announcement, “explosion hazard”, was made 294 seconds after the HGV stopped. The second announcement, “leave the tunnel”, was made after 424 seconds.

A.6.2 Results

The first persons to get out from the car ware L9 and L8, at 151 and 154 seconds respectively. They started to discuss the situation and L7 joined them after 15 seconds. The result of the discussion was that L8 went to an aid post and used the emergency phone.

Then nothing happened until the “explosion hazard” announcement was made. The announcement started a reaction among the motorists. Those who already were outside their cars started to walk to the exits and those who were in their cars stayed there for at least one minute and then they got out and left immediately for the exits. L2 made a U-turn and drove upstream in the tunnel while there were pedestrians crossing the driving lanes. He stopped next to Exit 7 and evacuated through it.

The last person left the car after 447 seconds, nearly 2 ½ minutes after the first announcement was made and one minute after all the other participants had left the tunnel. He was out after 460 seconds. The time from the moment the first person left the tunnel until the last one left it was 114 seconds. If the last person is not counted this time was 45 seconds.

Two motorists, L9 and L11, went back to their cars and locked them after they had already evacuated. This behaviour shows that people are afraid of leaving their belongings without sight unless they have arranged something for the security. L9 and L11 entered the tunnel with a burning HGV without further notice of the risk to lock their cars. Probably they valued the risk of getting the car stolen if it was unlocked as greater than the risk of entering the tunnel.

In the test the mean hesitation time was 65 seconds. The hesitation time was spent by those four persons who discussed and then used the aid station.

The mean walking speed was 1.4 m/s, which was close to the average, 1.37 m/s.

Four persons reacted before the announcement was made and they also called for help. Although they did not think that the situation was so threatening that they had to leave the tunnel immediately.

The second announcement "leave the tunnel" finally convinced the last person to leave the tunnel. When this announcement was made only one person was left in the tunnel.

All motorists chose the closest way to the emergency exits.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A9 below. The complete test record follows on next page.

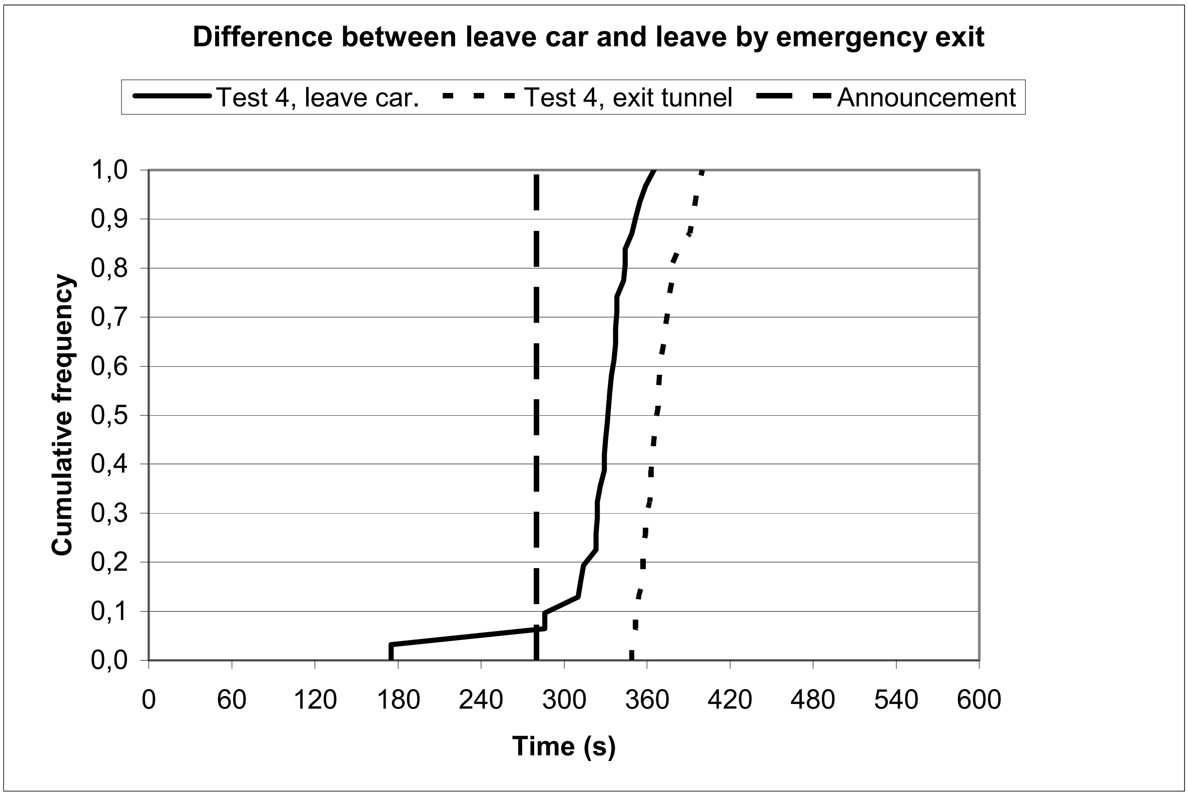


Figure A9 Motorists leaving the car and motorists leaving the tunnel.

Table A4 Test 4 (9 Jan)

Announcement: "explosion hazard" 294 sec

Announcement: "leave the tunnel" 424 sec

Counter starts (t0) 20:48:06

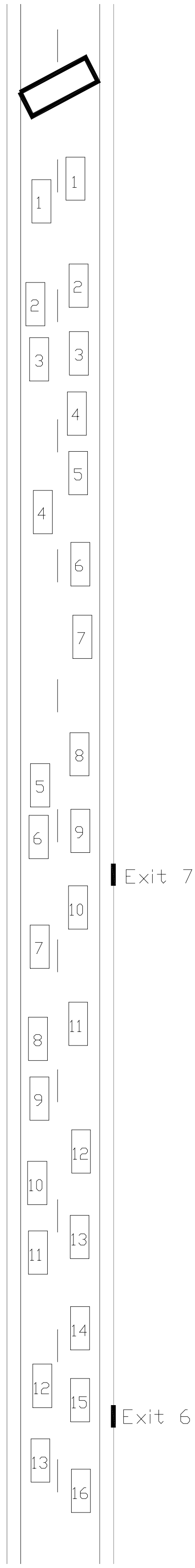
	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed (m/s)	Other
L1	Frontman (not counted)					
L2	362	369	0	5	0,7	Makes a U-turn at 328 s and drives back. Stops besides the exit 7.
L3	447	460	0	25	1,9	Starts reversing 15 meters at 440 s and then leaves his car.
L4	349	360	0	12	1,1	-
L5	328	346	0	18	1,0	-
L6	215	350	125	28	2,8	-
L7	168	365	184	34	2,6	Talks with L6, L8 and L9. Later he talks wih L10 and then returns to his car.
L8	154	346	164	31	1,1	Returns to the car and closes the door at 233 s. Walks to the emergency phone and picks it up and then walks to the exit 7 at 318 s. Walks from L2
L9	151	361	178	31	1,0	Stops to talk 175 s. Starts walking toward the emergency phone with L8 and then talks with L2. Walks from L2. Returns to car from emergency exit at 381 s. Back at car at 412 s. Leave car for exit 6 at 417s, out at 431 s.
L10	381	395	0	10	0,7	-
L11	372	387	0	13	0,9	First stops between the driving lanes, then parks in the left lane at 335 s. Two in car. Returns to the car at 433 s. Back at car at 445 s. Lock his car and leave at 464 s, out at 469 s.
sum	2927	3739	651	207	14	
mean	292,7	373,9	65,1	20,7	1,4	
std	103,9	32,6	81,0	9,8	0,74	

A.7 Test 5

A.7.1 Description of the test

Test 5 took place on the 10th of January at 19:15.

In the test 29 cars were viewable for the cameras. Excluding the frontman, R1, this means that 28 cars were analysed. The position for each car is shown in Figure A10 to the right.



The first announcement, “explosion hazard”, was made 378 seconds after the HGV stopped. The second announcement, “leave the tunnel”, was made after 528 seconds.

A.7.2 Results

The first person got out from his car after 393 seconds. Not a single action to leave the car was taken before the first announcement was finished; everyone stayed in his car. The only action noted at all was two drivers in the right lane that moved their cars to gaps in the left lane closer to the HGV.

As soon as the announcement was made, however, the evacuation ran fast and smoothly and all drivers did exit the tunnel through the emergency exits within less than 100 s.

The mean hesitation time in the test was only 6 s. Most of the drivers did not hesitate at all once they had opened their car doors; they started to walk towards the exits immediately.

The walking speed was close to the average walking speed; 1.3 m/s in the test compared to the total average of 1.37 m/s. (see Chapter 3)

When the evacuation took place drivers R13 to R16 in the right lane and drivers L11 to L13 in the left lane chose exit 6. The most logic decision would be to choose Exit 6 even for R12 and L10; by choosing Exit 7 the distance to the exit became a little longer.

The second announcement that the people should leave the tunnel did not matter for the result of the test since every person had left the tunnel when this announcement took place.

From the way that the drivers behaved in this test it is evident that they needed a confirmation that they were in danger and that they had to evacuate. The smoke from the truck was not enough to provide a confirmation. The people did not feel any treat from the smoke. Although when the announcement was made they started to evacuate quite fast.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A11 below. The complete test record follows on next page.

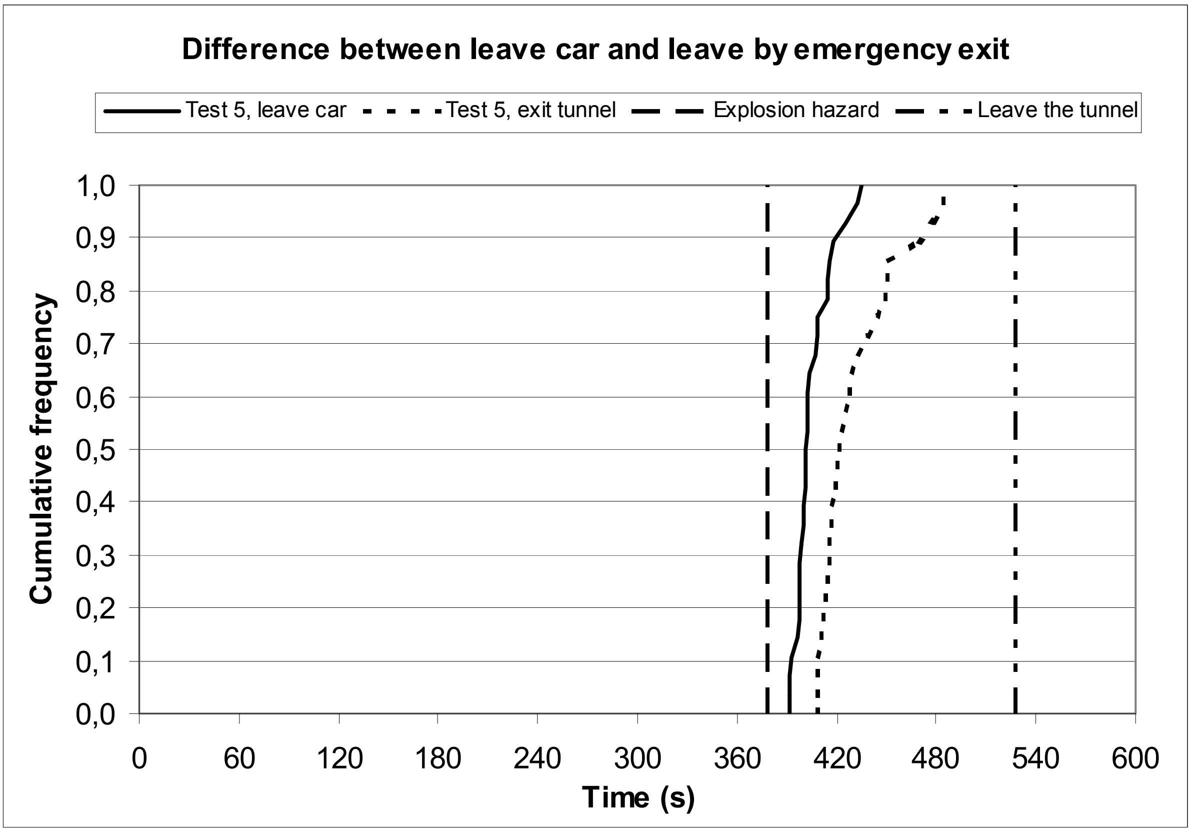


Figure A11 Motorists leaving the car and motorists leaving the tunnel.

Table A5 Test 5 (10 Jan)

Announcement: "explosion hazard" 378 sec

Announcement: "leave the tunnel" 528 sec

Counter starts (t0) 19:15:43

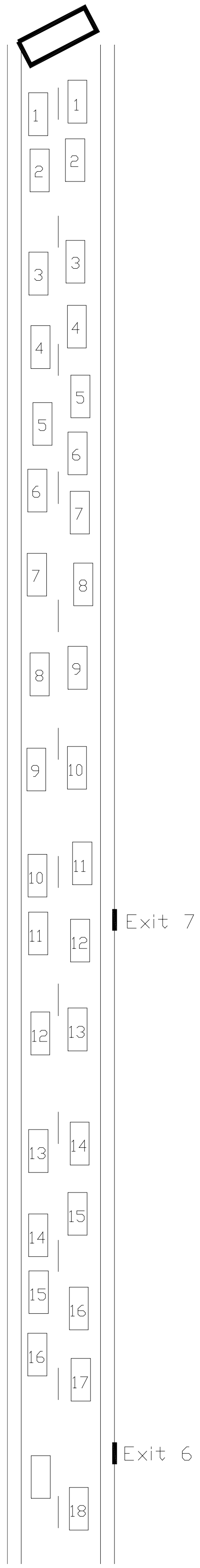
	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit (m)	Walking speed (m/s)	Other
L1	418	486	17	70	1,4	Goes back to car and turns it off.
L2	425	469	0	60	1,4	-
L3	416	452	0	56	1,6	Changes from right lane to left and comes closer the truck. Talks and hugs with R4 on the way to the exit
L4	392	409	0	41	2,4	Changes from right lane to left and comes closer the truck.
L5	391	408	0	16	0,9	-
L6	397	417	6	12	0,9	-
L7	399	413	0	15	1,1	-
L8	401	419	0	23	1,3	-
L9	401	420	0	29	1,5	-
L10	400	428	17	36	3,3	Turns off lights. Uses exit 7.
L11	407	445	16	23	1,0	Locks car. Uses exit 6.
L12	403	417	7	11	1,6	-
L13	401	414	0	12	0,9	-

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit (m)	Walking speed (m/s)	Other
R1	Frontman (not counted)					
R2	432	478	0	58	1,3	-
R3	435	484	10	52	1,3	-
R4	409	450	11	41	1,4	Goes to L3 and then to the exit. Talks and hugs with L3 on the way out. Walks from L4.
R5	414	449	7	41	1,5	-
R6	403	439	9	33	1,2	-
R7	408	425	0	26	1,5	-
R8	397	412	0	16	1,1	-
R9	400	411	0	9	0,8	-
R10	404	416	0	7	0,6	-
R11	393	409	0	18	1,1	-
R12	396	423	8	30	1,6	Locks car, uses exit 7.
R13	415	433	7	21	1,9	Locks car, uses exit 6.
R14	397	422	13	12	1,0	Walks over to L16 and discusses with that driver, then evacuates from that place.
R15	398	416	11	6	0,9	Hangs around close to car
R16	402	429	18	11	1,2	Locks car.

Sum	11354	12093	157	785	38
Mea	406	432	6	28	1,3
Std	11,2	23,2	6,3	17,9	0,52

A.8 Test 6

A.8.1 Description of the test



Test 6 took place on the 10th of January at 20:45.

In the test 33 cars were partly viewable for the cameras. One of them was the frontman and was therefore not analysed. Three of the other cars were impossible to analyse because of smoke blowing from the HGV towards the cars and the cameras. Thus the analysis was based on 29 cars. The position of each car is shown in Figure A12 to the right. In this test the smoke from the HGV spread out over the motorists instead of blowing away upstream in the driving direction as in the other tests.

The first announcement, “explosion hazard”, was made 372 seconds after the HGV stopped. The second announcement, “leave the tunnel”, was made after 462 seconds.

A.8.2 Results

Until the first announcement there was a total passivity among the drivers, nobody opened the door despite the smoke that reduced the visibility significantly.

The first person to get out of the car was L12 at 355 s after the HGV came to a halt. He walked to L13 and stayed there discussing for a short time before he returned to his car and stayed in it until he disembarked with the purpose of evacuating at 455 s after the HGV stopped. This was 77 s after the “explosion hazard” announcement was heard for the first time. By then the message had already been repeated twice.

Except for L12 the first one to react was R6 who put his foot on the ground after 411 s, 39 s after the start of the announcement. Several other drivers then started to react, some of them hesitated before evacuating while others decided to evacuate as soon as they had left their cars.

A few drivers waited for a long time before reacting. Especially those close to the HGV remained for a long time in their cars, not reacting until other drivers warned them. This was despite the fact that the smoke surrounding them became more and more dense. The drivers in five cars closest to the HGV did not react until more than 500 s had passed since the HGV stopped. (Participants in the front of the row had a CD playing in the car; this may be the reason for the delay of action since they perhaps did not hear the announcements.)

The first person to pass through the exit was R15 who left the tunnel after 449 s. This driver was then followed by most of the other drivers; within 50 s 21 more participants left the tunnel. Figure A13 and A14 shows the tunnel during the test.

Figure A13 The tunnel 1 minute after the HGV stopped

Figure A14 The tunnel 5 minutes after the HGV stopped. The motorists still sit in their cars.

The mean hesitation time in the test was 12 s. Most of the drivers did not hesitate at all once they had opened their car doors; they started to walk towards the exits immediately. Those hesitating for a longer time spent this time talking to other drivers.

The walking speed was close to the average; 1.4 m/s in the test compared to the total average of 1.37 m/s. (see Chapter 3)

In this test almost all participants stayed long enough in the tunnel to hear the second announcement. In this test it was the longer version of the announcements, telling the motorists to use the emergency exits. However, almost all of the participants seem to have decided before the announcement was made and because of this the message did not affect the evacuation time. Neither was there a significant higher walking speed in the tunnel even though most of the drivers heard the message shortly after leaving the car, when they were walking towards the exit.

From this test it is obvious that the danger the situation itself provided was not enough to make the participants evacuate. None of them decided to evacuate before the announcement was made whereas most of them decided to evacuate when they heard the first message. For a few not even the announcement was enough to make them evacuate.

Only one driver, L14, chose to walk to an exit that was not the closest one, Exit 7 instead of 6.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A13 below. The complete test record follows on next pages.

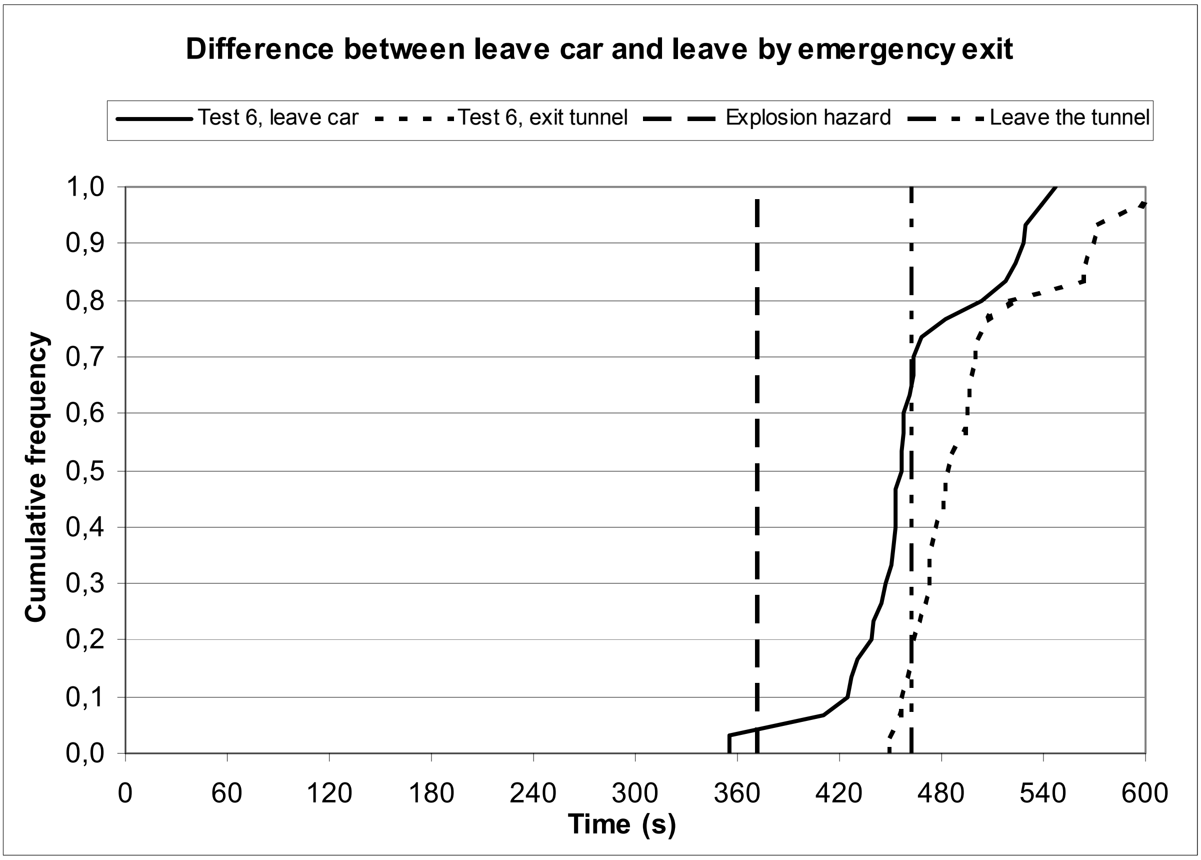


Figure A15 Motorists leaving the car and motorists leaving the tunnel.

Table A6 Test 6 (10 Jan)

Announcement: "explosion hazard" **372 sec**
Announcement: "leave the tunnel" **462 sec**
Counter starts (t0) 20:46:18

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
L1	Not viewable, in smoke.					
L2	547	606	19	78	2,0	-
L3	Not viewable, in smoke.					
L4	Not viewable, in smoke.					
L5	518	569	8	54	1,3	Locks the car
L6	482	508	0	48	1,8	-
L7	453	501	0	40	0,8	-
L8	439	495	32	31	1,3	Walks to L7 and then went back to his car and turns it off.
L9	504	521	6	22	2,0	-
L10	458	482	8	12	0,8	Locks car.
L11	461	481	0	10	0,5	-
L12	355	470	100	20	1,3	Leaves car to talk to L13. Then returns and stays in car until deciding to go to exit at 455 s.
L13	457	473	4	30	2,5	Locks car.
L14	431	457	5	38	1,8	Locks car. Uses exit 7.
L15	464	486	8	23	1,6	Locks car. Uses exit 6.
L16	453	476	0	17	0,7	-

	Leave car (s)	**Leave by em exit (s)**	**Hesitation (s)**	**Distance to em exit (m)**	**Walking speed (m/s)**	**Other**
R1	Frontman (not counted)					
R2	539	596	6	71	1,4	-
R3	528	573	5	66	1,7	-
R4	529	565	0	60	1,7	-
R5	523	564	5	53	1,5	-
R6	411	484	54	42	2,2	Talks with R7 and then went to emergency exit. Walk from R7.
R7	464	497	0	42	1,3	-
R8	447	500	23	35	1,2	-
R9	458	494	12	27	1,1	-
R10	445	498	31	18	0,8	Talks with R6 and then went back to his car and turns it off.
R11	468	474	0	9	1,5	-
R12	452	463	0	6	0,5	-
R13	450	460	4	15	2,5	-
R14	427	456	4	25	1,0	Locks car. Uses exit 7.
R15	425	449	9	26	1,7	Locks car. Uses exit 6.
R16	453	467	0	17	1,2	-
R17	440	462	14	11	1,4	Locks car.
R18	456	473	5	9	0,8	-

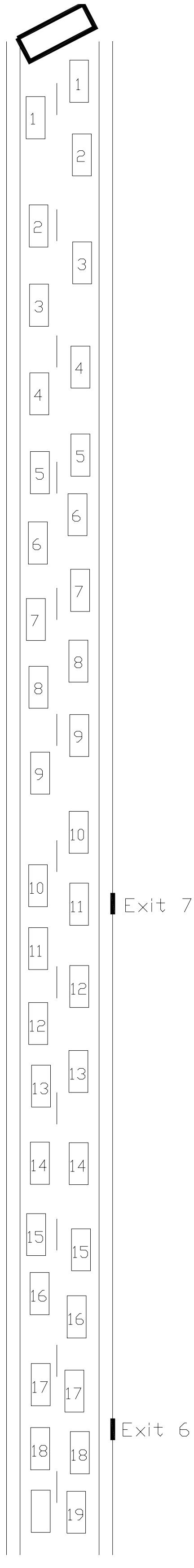
Sum	13937	15000	362	955	42
Mean	465	500	12	32	1,4
Std	41,1	43,2	20,2	19,6	0,53

A.9 Test 7

A.9.1 Description of the test

Test 7 took place the on 9th of January at 21:03.

In the test 37 cars were viewable for the cameras. Excluding the frontman, R1, this means that 36 cars were analysed. The position for each car is shown in Figure A16 to the right.



The first announcement, “explosion hazard”, was made 351 seconds after the HGV stopped. The second announcement, “leave the tunnel”, was made after 471 seconds.

A.9.2 Results

The first person, R19 got out from his car after 3 minutes. He walked to the car in front of his own and started talking with the driver. Then he returned to his own car. Then nothing happened until the first announcement was made. 20 seconds later several of the motorists started leaving their cars and almost all go direct to the exit without hesitation.

The last person left the car after 416 seconds and the tunnel was evacuated after 455 seconds, i.e. 104 seconds after the announcement.

In the test the mean hesitation time was 12 seconds. If R19 is not considered the mean hesitation time was 6 seconds. The hesitation time was spent on locking and turning off the cars.

The mean walking speed was 1.4 m/s, which was close to the average, 1.37 m/s.

Only one person reacted before the announcement. All the others sat tight in their cars although smoke came from the HGV.

The second announcement “leave the tunnel” was called into an empty tunnel.

All motorists chose the closest way to the emergency exits.

The cumulative frequencies for leaving the car and exiting the tunnel are shown in Figure A15 below. The complete test record follows on next page.

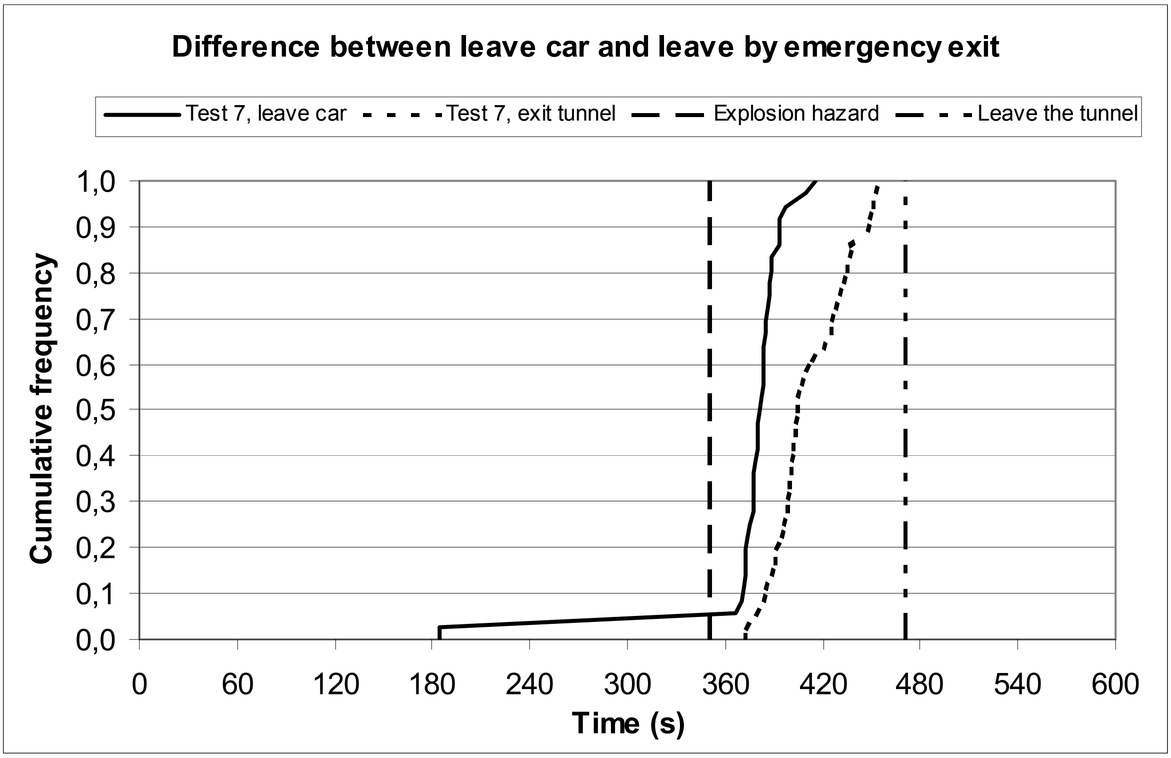


Figure A17 Motorists leaving the car and motorists leaving the tunnel.

Table A7 **Test 7 (16 Jan)**

Announcement: "explosion hazard" **351 sec**

Announcement: "leave the tunnel" **471 sec**

Counter starts (t0) 21:03:40

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed (m/s)	Other
L1	387	452	0	82	1,3	-
L2	380	438	0	72	1,2	-
L3	373	420	0	65	1,4	-
L4	378	435	0	56	1,0	Two in car.
L5	382	436	9	49	1,1	Locks car.
L6	374	430	33	42	1,8	Turns off and locks his car
L7	373	433	24	35	1,0	Turns off and locks his car
L8	389	425	18	28	1,6	Discusses with other people around him.
L9	394	428	13	20	1,0	Discusses with other people around him.
L10	367	372	0	10	2,0	-
L11	375	385	0	12	1,2	-
L12	377	391	6	20	2,5	Locks car.
L13	377	395	4	26	1,9	Locks car.
L14	384	402	4	33	2,4	Locks car. Uses exit 7.
L15	381	403	0	26	1,2	Uses exit 6.
L16	380	398	5	31	2,4	-
L17	370	384	5	12	1,3	-
L18	386	404	0	10	0,6	-

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed (m/s)	Other
R1	Frontman (not counted)					
R2	387	449	9	76	1,4	-
R3	416	455	0	65	1,7	-
R4	384	451	18	55	1,1	Walks around L4 and back locking his car.
R5	394	448	22	47	1,5	Locks his car
R6	372	399	0	41	1,5	-
R7	383	403	0	34	1,7	-
R8	379	396	0	27	1,6	-
R9	383	398	0	20	1,3	-
R10	385	401	5	11	1,0	-
R11	371	379	0	6	0,8	-
R12	410	425	0	12	0,8	-
R13	393	410	6	20	1,8	Locks the car.
R14	388	404	4	29	2,4	Locks the car. Uses exit 7.
R15	397	413	7	21	2,3	Locks the car. Uses exit 6.
R16	385	401	7	15	1,7	Locks the car.
R17	377	389	5	8	1,1	Locks the car.
R18	380	391	0	6	0,5	Two persons in the car.
R19	184	407	210	12	0,9	Talks to L18, then returns to own car.

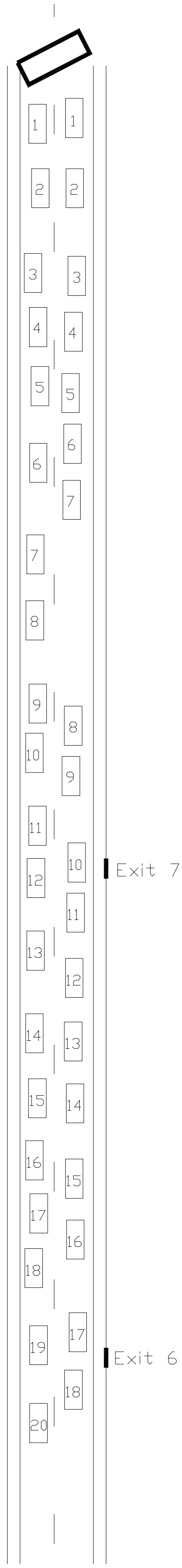
Sum	13595	14850	414	1134	52
Mean	378	413	12	32	1,4
Std	34,3	22,5	34,5	21,1	0,52

A.10 Test 8

A.10.1 Description of the test

Test 8 took place on the 11th of January at 19:15.

In the test 38 cars were viewable for the cameras. Excluding the frontman, R1, this means that 37 cars were analysed. The position for each car is shown in Figure A18 to the right.



This test was thought to be a control test and the motorists were told to evacuate as soon as they stopped in the tunnel. However, the message was not clear enough and it took some time until they started to evacuate.

A.10.2 Results

The first person got out from the car 49 seconds after the HGV stopped. Then the rest followed and the last person left the car after 127 seconds. Several motorists did not know what to do and they stayed next to their cars or walked around trying to figure out what to do. After quite some time they started to move to the exits. The first person left the tunnel after 99 seconds and after 185 seconds the tunnel was empty.

The purpose of the test was to analyse the flow rate at the doors and therefore the area close to the exits should have been crowded. However, since the persons in the test did not immediately go to the exits, this area was never crowded. Therefore the walking peed of this test is possible to analyse.

The mean walking speed was 1.2 m/s, which is slower than the average, 1.37 m/s, for test 1-7.

All motorists chose the closest way to the emergency exits.

Table A8 Test 8 (11 Jan)
Counter starts (t0) 19:15:55

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit (m)	Walking speed (m/s)	Other
L1	49	165	24	80	0,9	Talks to frontman. Walks from R1.
L2	56	128	3	78	1,1	Locks the car
L3	66	132	16	69	1,4	Turns off the car.
L4	76	115	4	64	1,8	-
L5	84	117	0	57	1,7	-
L6	94	134	5	49	1,4	Locks the car
L7	101	148	6	40	1,0	Locks the car
L8	111	185	0	33	0,4	-
L9	112	153	18	25	1,1	Locks the car
L10	127	155	13	20	1,3	Hangs on car door. Locks car.
L11	91	106	0	13	0,9	-
L12	82	99	10	10	1,4	Locks the car.
L13	86	120	25	16	1,8	Locks the car.
L14	124	158	10	25	1,0	-
L15	112	151	7	34	1,1	Uses exit 7.
L16	111	152	20	28	1,3	Walks around and locks his car. Uses exit 6.
L17	88	120	8	23	1,0	-
L18	104	142	16	17	0,8	Locks the car
L19	100	139	20	10	0,5	Locks the car
L20	109	144	13	15	0,7	Locks the car

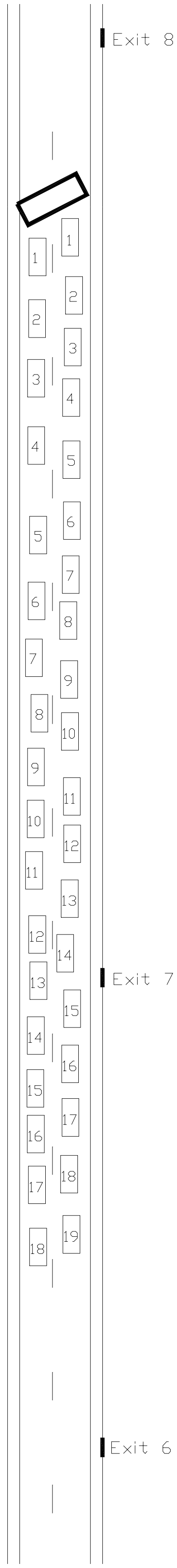
	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit (m)	Walking speed (m/s)	Other
R1	Frontman (not counted)					
R2	66	140	10	74	1,2	-
R3	69	138	19	65	1,3	-
R4	72	108	20	59	3,7	-
R5	90	151	10	52	1,0	Locks his car.
R6	84	205	98	47	2,0	Goes up and down. Returns after she nearly has reached the exit.
R7	88	137	16	42	1,3	-
R8	120	161	29	19	1,6	Hangs on the car door
R9	79	98	3	14	0,9	-
R10	90	102	4	6	0,8	Locks his car.
R11	100	112	7	9	1,8	Locks his car.
R12	123	155	5	15	0,6	Locks his car.
R13	84	119	14	22	1,0	Uses exit 7.
R14	120	159	22	30	1,8	Opens the car door and grabs the jacket. Locks the car. Uses exit 6.
R15	95	161	50	22	1,3	Walks around his car. Talks with R14 and runs out with her.
R16	104	124	10	16	1,6	Locks his car.

A.11 Test 9

A.11.1 Description of the test

Test 9 took place on the 11^{th} of January at 20:47.

In the test 37 cars were viewable for the cameras. Excluding the frontmen R1, R19 and L18, this means that 34 cars were analysed. The position for each car is shown in Figure A19 to the right.



This test was thought to be a control test and the motorists were told to evacuate as soon as they stopped in the tunnel. In this test the information that the participants should leave the tunnel immediately was underlined.

A.11.2 Results

The reaction when the drivers stopped was instantaneous. Before all cars even had stopped the first person stepped out from his car. The rest followed just after. All motorists walked towards the exits as soon as they got out from their cars. Not a single one hesitated. After 82 seconds the tunnel was evacuated.

The area next to Exit 7 became crowded when all people should pass the door at the same time. This did not made the total evacuation time longer because when the last persons reached the exit it was not crowded. However, this fact slowed down the walking speed since the walking time is defined to be the time until the motorist exited the tunnel. Some drivers also slowed down when they saw that there was a crowd outside the door. These facts made it impossible to estimate a “control walking speed”.

The mean walking speed was 1.1 m/s in this test compared to the average of test 1-7, 1.37 m/s. To reach the average 3 seconds must be subtracted from every person in the test, which can be a good estimation of the time they waited outside the exits. Therefore this test too provides a good comparison to the average in Tests 1-7.

L1, L2 and R2 chose the exit closest to them, Exit 8, but they had to pass the HGV. All the other drivers went to Exit 7, which is the closest exit downstream the HGV.

Table A9 Test 9 (11 Jan)

Counter starts (t0) 20:47:37

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed	Other
L1	22	47	0	32	1,3	Uses exit 8.
L2	18	49	0	38	1,2	Uses exit 8.
L3	17	82	0	103	1,6	Walks round R1 and then evacuate by exit 7.
L4	19	82	0	111	1,8	Walks round R1 and then evacuate.
L5	26	73	0	55	1,2	-
L6	24	62	0	48	1,3	-
L7	31	76	0	42	0,9	-
L8	25	49	0	36	1,5	-
L9	30	50	0	30	1,5	-
L10	29	48	0	25	1,3	-
L11	34	52	0	19	1,1	-
L12	36	56	0	13	0,7	-
L13	32	41	0	11	1,2	-
L14	40	69	0	14	0,5	-
L15	46	78	0	20	0,6	-
L16	48	79	0	25	0,8	-
L17	48	81	0	30	0,9	Uses exit 7.
L18	Frontman (not counted)					

	Leave car (s)	Leave by em exit (s)	Hesitation (s)	Distance to em exit	Walking speed	Other
R1	Frontman (not counted)					
R2	8	28	0	32	1,6	Uses exit 8
R3	19	42	0	71	3,1	Uses exit 7.
R4	15	66	0	66	1,3	-
R5	19	69	0	59	1,2	-
R6	20	60	0	52	1,3	-
R7	24	64	0	47	1,2	-
R8	29	72	0	42	1,0	-
R9	30	58	0	36	1,3	-
R10	32	59	0	30	1,1	-
R11	35	69	0	23	0,7	-
R12	36	54	0	18	1,0	-
R13	37	45	0	12	1,5	-
R14	35	43	0	7	0,9	-
R15	39	47	0	8	1,0	-
R16	44	61	0	13	0,8	-
R17	44	75	0	19	0,6	-
R18	46	71	0	25	1,0	Uses exit 7.
R19	Frontman (not counted)					

Sum	1037	2057	0	1212	40
Mean	28,8	57,138889	0	33,7	1,1
Std	10,27	19,28	0	24,20	0,46

A.12 Analysis of data

A.13 Method to estimate distributions

The method used to estimate the best-fitted distribution is a MATLAB- toolbox for analysis of random waves and loads called WAFO, developed by the Center for Mathematical Sciences at Lund University, WAFO (2002). The toolbox was developed for analysis of ocean waves but can also be used to calculate theoretical distributions from random values like those in the tests in the Benelux tunnel.

The used distributions in the analyses are Normal distribution, Gumbel distribution and Generalized Extreme Value distribution. Lognormal and Weibull distributions are also tested but they did not fit.

Normal distribution has the distribution function

Normal: $F(x;\mu,\sigma) = \dfrac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2}$, $-\infty<x<\infty$.

To estimate the best-fitted normal distribution WAFO uses the Maximum Likelihood Method (ML).

Gumbel distribution has the distribution function

Gumbel: $F_G(x;a,b) = \exp(-e^{-(x-b)/a})$, $-\infty<x<\infty$.

To estimate the best-fitted Gumbel distribution WAFO uses the Maximum Likelihood Method (ML).

Generalized Extreme Value distribution has the distribution function

GEV: $F(x;k,\mu,\sigma) = \exp\{-(1-k(x-\mu)/\sigma)^{1/k}\}$, $0<x<\sigma/k$ if $k>0$

To estimate the best-fitted GEV-distribution WAFO uses Probability Weighted Moments (PWM).

To test which distribution that fits best chi-square tests were made. This was made in the toolbox Best Fit in Decision Tools, Palisade (1997). The Generalized Extreme Value distribution is not represented in the Best Fit toolbox and the chi-square value is calculated by hand.

The results from the chi-square tests are shown in the table below. Every stage has been checked with five distributions; Normal, Lognormal, GEV, Gumbel and Weibull.

Table A10. Chi-square values as indication of goodness of fit for the different observed distributions (best fit are bold).

	Leave car before 1	Leave car before 2	Leave car after PA*	Hesitation before PA*	Hesitation after PA*	Walking speed
Normal	**1.63**	10.79	168.6	**2.86**	$2.8 \cdot 10^{8}$	29.65
Lognormal	2.39	7.53	12.83	20.23	43.19	13.90
GEV	2,16	8,32	**7.49**	6.79	**13.25**	15.53
Gumbel	2,83	**5,97**	20.97	7.28	142.9	**13.71**
Weibull	1,83	10,41	24.27	3.87	168.6	19.37

* PA= public announcement

APPENDIX B – TRAIN TUNNEL TEST

B.1 Test results

Table B1 The results from each test that were made.

Kastrup station

Test	N persons	Door width (m)	Time (s)	Flow (pers/s)	Vertical distance (m)	Note
1	33		52	0.635	0.3	
2	20	1.37	21	0.952	0.5	old danish train
3	13		14	0.929	0	
4	15		23	0.652	0.3	
5	30		68	0.441	0.3	school group with luggage
6	27		42	0.643	0.3	
7	14		16	0.875	0	
8	17		19	0.895	0	
Sum	**169**					

Schiphol Station

Test	N persons	Door width (m)	Time (s)	Flow (pers/s)	Vertical distance (m)	Note
1	15	1.07	22	0.682	0.3	
2	16	>1.40	14	1.143	0.3	
3	16	1.27	15	1.067	0.3	
Sum	**47**					

Best exercise

Camera	N persons	Door width (m)	Time (s)	Flow (pers/s)	Vertical distance (m)	Note
1	37	1.27	41	0.90244	0.7	
2	12	1.27	21	0.57143	0.7	
3	10	1.27	14	0.71429	0.7	
4	6	1.27	4	1.5	0.7	
5	3	1.27	4	0.75	0.7	
6	18	1.27	34	0.52941	0.7	
Sum	**86**					

Utrecht station

Test	N persons	Door width (m)	Time (s)	Flow (pers/s)	Vertical distance (m)	Note
1	26	1.07	27	0.963	0.3	
2	24	0.88	35	0.686	0.3	
3	19	1.27	23	0.826	0.3	Only half the door in use
4	7	1.27	8	0.875	0.3	
5	49	1.07	48	1.021	0.3	
6	27	0.88	33	0.818	0.3	
7	20	0.88	27	0.741	0.3	
8	59	1.27	57	1.035	0.3	
9	30	0.88	38	0.789	0.3	
10	26	1.27	25	1.040	0.3	
11	20	0.88	26	0.769	0.3	
12	19	0.73	40	0.475	0.3	
13	18	1.27	26	0.692	0.3	
14	10	1.27	13	0.769	0.3	
15	11	0.90	18	0.611	0.3	ICE
16	7	1.27	13	0.538	0.3	
17	17	0.77	23	0.739	0.3	
18	5	0.90	14	0.357	0.3	ICE
19	21	1.27	33	0.636	0.3	Bike blocks half the door
20	5	1.27	5	1.000	0.3	
21	5	0.90	7	0.714	0.3	ICE
22	21	1.27	42	0.500	0.3	
Sum	**446**					

Stockholm

Test	Door	N persons	Door width (m)	Time (s)	Vertical distance (m)	Flow (pers/s)
1	1	14	1.30	7	0	2.000
1	2	6	1.30	5	0	1.200
1	3	8	1.30	5	0	1.600
2	1	7	1.30	3.5	0	2.000
2	2	6	1.30	3.5	0	1.714
2	3	6	1.30	3.5	0	1.714
3	1	4	1.30	2	0	2.000
3	2	9	1.30	6	0	1.500
3	3	3	1.30	2	0	1.500
4	1	8	1.30	6	0	1.333
4	2	6	1.30	5	0	1.200
Sum		**77**				

Stockholm exercise Frantzich (2000)

Test	Door width (m)	Vertical distance (m)	Flow (pers/s)	Note
1	1.20	1.2	0.1-0.2	Total dark in the tunnel
2	1.20	1.2	0.4-0.6	Light in the tunnel

B.2 Figures

Figure B.1 A disembarking from an Inter City train in Utrecht.

Figure B.2 A disembarking from an Inter City train in Kastrup.

Figure B.3 A disembarking from a two-storey-train in Utrecht.

Figure B.4 The counter starts when the first person puts his foot on the ground