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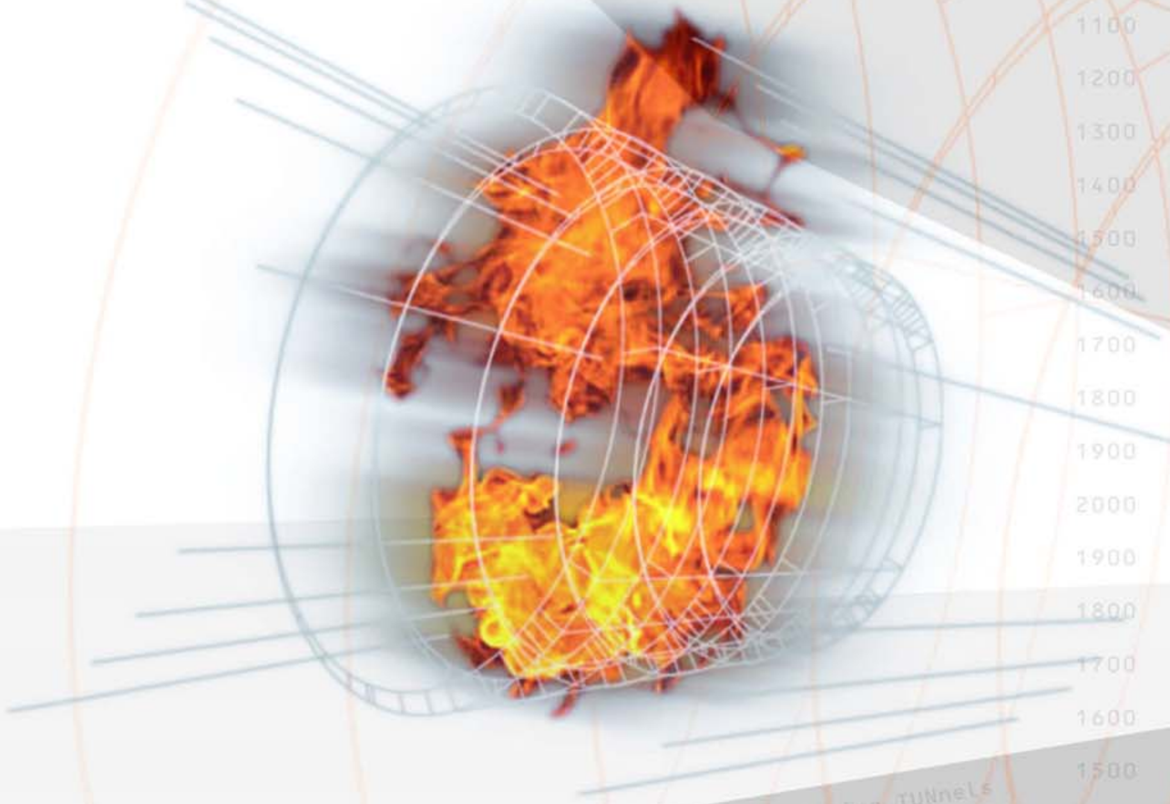
Workpackage 3 Human response
D33

Human Factors Aspects in Tunnels: Tunnel User Behaviour and Tunnel Operators



Authors

Marieke Martens

TNO

with contribution from all partners (Martens was editor)

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UPTUN

UPTUN is an acronym for the title of a research project carried out in the scope of the 5th Framework Programme of the European Commission, under contract G1RD-CT-2002-766. UPTUN stands for: "Cost effective sustainable and innovative UPgrading Methods for Fire Safety in existing TUNnels". In the project, officially started September 1st 2002 and officially closed August 31st 2006, 41 partners out of 19 EU member states participated and closely worked together in a joint effort to overcome fire safety issues emerging from the tragic Alpine tunnel accidents in the years 1990-2000.

UPTUN's objectives were:

1) **Development of innovative methodologies and technologies where appropriate and, where relevant, comparison to and assessment of existing methodologies and technologies for tunnel application. New technologies have been developed: water mist, water curtains, smoke compartmentation, CCTV detection techniques, training tools and programs, repair mortars and software assessment tools, including local and regional cost effect models.**
2) **Development, demonstration and promotion of procedures for rational safety level evaluation, including decision support models and knowledge transfer. Safety level assessment criteria were drawn up and integrated in manual and automatic upgrade procedures/models. Knowledge was transferred through dissemination on various levels: papers and presentations, international symposia (Prague, Lausanne), dedicated workshops throughout Europe and beyond (Australia, China, USA) and the establishment of a manual for good practice and an UPTUN summer course.**

The desired spin-off was the restoration of faith in tunnels as safe components of the transportation systems, the levelling out of trade barriers imposed by supposedly unsafe tunnels, and an increased awareness of stakeholders of the necessity to develop initiatives to link all relevant research.

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COMPETITIVE AND SUSTAINABLE GROWTH PROGRAMME

UPgrading of existing TUNnels

Project No: GRD1-2001-40739

Work Package 3

Human response

Task 3-2 and 3-3

Review of State-of-the-Art and Interrelation with Other Projects

Deliverable 3.3

Human Factors Aspects in Tunnels: Tunnel User Behaviour and Tunnel Operators

WP leader Marieke Martens (also Editor)

TNO Human Factors

<u>Contributing Partners:</u> TNO (NL) – RWS (NL) - SINTEF (N) - BRE (UK) - MRSL (UK) - Maribor (Si)

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Annemiek van Waterschoot (RWS, NL)

Jeremy Fraser-Mitchell (BRE, UK)

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David Brenkley, John Ellis and David Gibson (MRSL, UK)

Tomaz Tolazzi and Vlasta Rodosec (University of Maribor, Si)

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Jean-Christophe leCoze (INERIS, Fr)

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CONTENTS

SUMMARY

Accidents in road tunnels came into the focus of public attention mainly during the last few years, after the tragic accidents in a number of European tunnels. Because of the confined environment accidents in tunnels, particularly fires can have dramatic consequences. The number of accidents in tunnels is relatively low in comparison with other segments of road environment, but their consequences can be much more serious. The main causes of accidents are incorrect behaviour of road users, inadequate infrastructure and operation, vehicle defects and problems with loads such as chemical reactions.

This Deliverable 3.3 is produced in the framework of UPTUN Work Package 3 (Human Response). The main objective is to find, develop, evaluate and promote new methods and means to remove, neutralise, or correctly assess factors, which contribute to a negative human response in incidents and accidents. In this, incidents are important since larger accidents always result from smaller incidents and accidents require special attention since they result if no adequate action is taken to an incident. In this respect, human behaviour regards the role a person has in a possible tunnel accident; as a road user, as an operator, or as a member of a rescue team. A review of the role of human behaviour can be found in Deliverable 3.2 of the UPTUN project. In WP3, Task 3.2 focused on the road user and the behaviour of road users in case of accidents. Task 3.3 focused on the role of the tunnel operator in the management of the incident. The objective of Task 3-3 is to analyse the task of the operator, including the interactions with tunnel users and rescue teams. The objective is also to collect and / or generate means of support for the operator, based on the above mentioned analysis. This deliverable describes the studies performed under these two tasks.

This deliverable describes the road from human causes of traffic accident, via behavioural studies to evacuation support and evacuation models and ends with the role of the operator and possibilities for improving the role of the operator in the process. Driving simulator studies showed that information is crucial in improving responses, although correct understanding of the situation seems to be hard to accomplish. Even though the EU-leaflet may help, more information needs to be provided. People in fire are ‘prone to normalcy’, to inaction, while panic is very rare. This finding is valid also in tunnels, as revealed in the UPTUN studies. An additional problem in fire is low visibility due to smoke. Therefore use of directional sound at emergency exits is recommended. A prototype of an innovative evacuation system was developed for UPTUN, using information from the behavioural studies. The evacuation model CRISP was updated with information from the different studies, focusing on the different groups of people and specific conditions. Safety of road users depends also on action of the tunnel’s staff and some findings on crisis management are therefore presented. Suggestions for prevention of accidents and mitigation of their consequences are presented. With respect to the tunnels operator, the COLFUN framework was used to describe the tasks and the mental load of operators in process control environments. This model was used identify problems that can occur within the work of tunnel operators and to define solutions for these problems.

This study is part of the UPTUN project (Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels), performed within the 5th framework program of the European Commission (see also www.uptun.net). The UPTUN project aims at the development and promotion of innovative, sustainable and low-cost measures to limit the probability and consequences of fires in existing tunnels, as well as the development and promotion of an integrated evaluating and upgrading procedure. Through this procedure, owners, stakeholders, designers, operators and emergency teams will be able to assess and upgrade the human and structural safety level. This deliverable is a summary of the work being done in Task 3.2 (tunnel user) and Task 3.3 (tunnel operator).

Preface

The European economy relies upon a sustainable transportation system. In this system, traffic has grown more significantly and changed in composition (more combustible and flammable goods), leading the last decades to a general reappraisal of the European safety standards. As tunnels are part of this transportation system, their safety level affects the overall safety level of the system. Since several years, the safety level in tunnels has received quite some international attention. In particular the fires in the alpine tunnels at Mont Blanc 1999 (39 fatalities), Tauern 1999 (12 fatalities) and Gotthard 2001 (11 fatalities) have highlighted shortcomings in the level of safety inside existing road tunnels. Rail and metro tunnels have also come under scrutiny, with the recent fire in the metro in Taegu (197 fatalities), and the metro fire in Baku, Azerbaijan, in 1995 (289 fatalities) being of particular note. While not a 'conventional' road or rail tunnel, the loss of 158 lives in the Kaprun ski-resort tunnel in 2000 emphasised dramatically the dangers inherent in tunnel systems. In these discussions, the role of human behaviour has always been important. In the international press, a lot of attention is paid to losses of human life. Tunnel users that are found burnt in their car, tunnel users that do not respond quickly enough to the emergency situation, tunnel operators that did not take the appropriate action. But how can we actually keep these dramatic situations to minimum?

The content of this deliverable will be as follows:

- Chapter 1: Introduction. Description of the problems associated with the human factor in tunnel safety. In this, the accident happening model will be presented, as well as a general framework of the issues associated with the tunnel user and incident handling. This chapter will be used to set the basis for the studies and tools developed in Task 3.2 (tunnel user) and 3.3 (tunnel operator).
- Chapter 2 describes the different stages a road user normally encounters when being in an incident. This chapter describes 2 driving simulator studies that tried to identify the reasoning processes of that tunnel user when deciding something is dangerous or not (phase before betting out of the car)
- Chapter 3 describes 2 evacuation studies that were being performed to identify the evacuation process after getting out of the car or bus or getting out of a metro. In Chapter 3, several studies were combined, looking into possibilities to support the tunnel user in finding their way, and also to look into details of evacuation speed, speed of getting out of trains and speed of walking up escalators.
- Chapter 4 describes an evacuation model that was begin updated for the UPTUN project in order to better describe the evacuation process in tunnels. Information from the studies performed in Chapter 3 was put into this mode. Chapter 4 describes how this model was begin updates and described some of the improved processes.

- Chapter 5 Describes a prototype that was made for this project of an innovative evacuation system, helping people to find their way in a dynamic fashion, taking temperatures and smoke into account. Knowledge also from the evacuation studies were taking into account.
- Chapter 6 describes the role of the tunnel operator in making decisions in critical situations inside tunnels, current guidelines and the possibilities for support
- Chapter 7 summarises the lessons to be learnt from Task 3.2 and 3.3.

M. Martens

WP3 leader and Editor

1. INTRODUCTION

A. van Waterschoot
Rijkswaterstaat, the Netherlands

G. Jenssen, M. Terje & C. Bjorkli
Sintef, Norway

D. Brenkley, J. Ellis & D. Gibson
MRSL, UK.

T. Tolazzi & V. Rodosec
University of Maribor, Slovenia

E. Konrad, M. Polic & A. Sabadin
Univerisity of Ljubljana, Slovenia

J. Fraser-Mitchell
BRE, UK

J. leCoze
INERIS, France

L. Boer, S. van Wijngaarden, J. Rypkema & M. Martens.
TNO Human Factors, the Netherlands

Accidents in road tunnels came into the focus of public attention mainly during the last few years, after the tragic accidents in Mont Blanc, Tauern and St. Gotthard tunnels. Because of the confined environment accidents in tunnels - particularly *fires* - can have dramatic consequences. On the other hand the number of accidents in tunnels is relatively *low* in comparison with other segments of road environment, for instance since tunnels are not exposed to adverse weather conditions (e.g. snow, ice, wind, rain), especially the longer ones. However, if fires do occur, consequences may be serious.

According to international statistics, the majority of vehicle fires are not caused by accidents in themselves, but rather by stand-alone causes of individual vehicles or its load due to defects in electrical systems or overheated engines (Commission of the EC, 2002). Nevertheless it must be mentioned that fires with the most serious consequences (e.g. injuries, fatalities, extensive material damage) have mostly been the result of accidents (12 out of the 14 worst fires known world-wide), with the exception of the Mont Blanc tunnel fire, which was caused by self-ignition of a heavy goods vehicle (Commission of the EC, 2002). A number of lessons were learned from these accidents, eventually ending in various recommendation, standards and directives concerning structural and technical installations or their operation, emergency services, but also demanding correct behaviour of road users. In this deliverable human behaviour with regard to the tunnel safety will be discussed. On one side there is road user behaviour causing the accidents, on the other there is the human behaviour involved in handling the accident with all associated risks. There are three groups of people that are of interest here: tunnel users, tunnel operators and emergency response teams. Behaviour relating to the first two categories (tunnel user and tunnel operator) are the main focus of this deliverable. The behaviour of the emergency response teams will be the subject of Task 3.4, resulting in another deliverable.

Tunnels are part of the traffic system, constructed for achievement of specific human purposes. Traffic is not merely technical system because it is used by people. This interaction of technical and human part of traffic system creates the problems of safety. New technological solutions that improve the efficiency of the traffic system create new safety problems at the same time.

We believe that the human part of the tunnel system relates to three stakeholders:

- *Tunnel designers*

This category includes designers, engineers and researchers from different backgrounds that design the technical and economic characteristics of tunnel's infrastructure. In relation to the physical characteristics of that infrastructure the designers also propose a system of rules for safe use of that infrastructure. These rules have implication for the role of other tunnel stakeholders

- *Tunnel operators*

This category includes the controller of the tunnel traffic (including police), maintenance and emergency response teams. These staffs care for implementation of rules defined by designers and general traffic rules. They help the tunnel users with information, which enable safe use of the tunnel. Maintenance staffs continually and periodically perform work planned for technical maintenance of the tunnel. Emergency response teams intervene in the case of disturbance and accident in tunnel. All the above staff is part of an organization that is structured and managed for effective achievement of goals defined by designers.

- *Tunnel users*

This category comprises drivers of different vehicles and their passengers. Drivers use their vehicles in accordance with rules put forth by designers, taking in account the characteristics of the current situation in tunnel and characteristics of their vehicles. Beside this the drivers must take in account the behaviour of other drivers in tunnel. We can say that most information that influences the driver behaviour is shaped by subjective interpretation of the driver.

Each of above stakeholders has a specific role in the operation of the tunnel. These roles are interdependent. Bad coordination of these roles and mutual misunderstandings can contribute to errors and eventually to accidents.

1.1 Importance of safety in tunnels

An insight into the importance of the road tunnels for EC and risk connected to their use as well as the costs of accidents are presented in excerpts from the EC Memorandum: Safety in European Road Tunnels:

THE TRANS-EUROPEAN TRANSPORT NETWORK (TEN-T)
(From Memorandum of the European Commission, Directorate General for Energy and Transport)

The trans-European transport network (TEN-T) has a crucial role in securing the free movement of goods in the European Union. It carries about half of all freight and passengers. Risks have **increased** in recent years with the **ageing** of tunnels. Most tunnels have indeed been built to specifications that with time have become outdated. Either their equipment no longer corresponds to the state of the art or traffic conditions have significantly changed since their initial opening. There is moreover no general mechanism at national level to oblige tunnel managers to improve safety once the tunnels are put into service. Tunnel users have **changed**. The risk of serious **fires** has significantly increased in recent years, due to the more intensive use of tunnels, and in **bi-national** tunnels in particular, **lack of co-ordination** between both sides. Moreover, serious accidents have shown that **non-native** users are at greater risk of becoming a victim in an accident, due to the lack of harmonisation of safety information, communication and equipment.

The European Commission proposed on December 30, 2002, a new Directive to achieve a uniform, constant and high level protection for all European citizens on Trans European Road Networks tunnels. **Absence** of action is detrimental since accidents in tunnels have proven to be extremely costly in many respects. The main causes of accidents are **incorrect behaviour** of road users, **inadequate infrastructure** and **operation**, vehicle **defects** and problems with **loads** such as chemical reactions.

(More information at the following address : http://europa.eu.int/comm/energy_transport/en/lb_en.html)

1.2 General approaches to traffic safety

Historically, mainly engineering approaches to safety in work and traffic prevail. Safety of processes and product was regarded as one of the more important criteria for the evaluation of technical solution besides the criteria of its utility and economy. Gradually the researchers increasingly acknowledge the role of organizational factors for the safety. This change in emphasis is related to the way the nature of risk is considered. A fundamental premise of much of the literature on accidents and risk defines safety as antithesis of error, or as negation or absence of risk (INSAG, 1991). This definition is embedded in the classic engineering definition of risk as a product of hazard (potential consequences) and probability of its occurrence. The task of safety research is the estimation of the probabilities of errors. Different complex procedures are used to estimate the risk (probability of error occurrence) of particular elements of the system, among them also human or behavioural elements. The risks that are above some level of acceptance are aimed to be eliminated or decreased with technical reconstruction or by means of changing human behaviour.

The aforementioned objective approach to risk produces useful results even though it neglects the social dimension of safety. It does not map well on to the world of human action, the main focus of WP3 in UPTUN. It does not deal with the issue of whether such a risk is acceptable to the human operator, to the organization, to legislator, or to general public. Human response to risk always depends on perception of risk, not on its objective calculation. The technical calculations of risk are filtered on the basis of subjective perception of safety. These interpretations are socially conditioned with our life (or work) experiences. People do not behave in accordance with the objective estimates of risk. Many people are afraid to fly even if we can prove that the objective risk of driving is greater as the objective risk of flying. Such human reactions are very common in different dangerous activities.

It is possible to correct the liabilities of the objective approach to the risk with a contingent valuation of risk. The approach is elaborated with definitions of different categories of risk perception. Some authors (Starr, 1969) propose dividing the risk exposure to voluntary and involuntary. This approach was intended to preserve the positivist paradigm of rational calculation in planning. It became clear that the problem of risk does not only concern the objective nature of the situation, but it is necessary to include different human characteristics as whether the individual believes that he is in control of the risk-producing activity, or can only react to it, the individual risk propensity and with whom the individual compares himself in relation to safety. It is this subjective aspect that needs to be integrated in a human factors' approach. As

Rochlin (1999) claimed: Risk as a construct of the human imagination overlaying on the surrounding world. This does not mean that the objective approach to the risk is wrong but that our responses, beliefs and actions are not shaped on objective data alone.

1.3 Road tunnels in Europe

In Europe there are many road tunnels (see Figure 1.1), due to its ground configuration and necessary transport routes and connections. From the safety point of view especially longer tunnels are important. Therefore the Commission proposes that all tunnels *longer than 500 meters in operation, under construction or at the design stage* and belonging to the *Trans European Road Network (TEN)* should be subject to the new harmonised safety requirements.

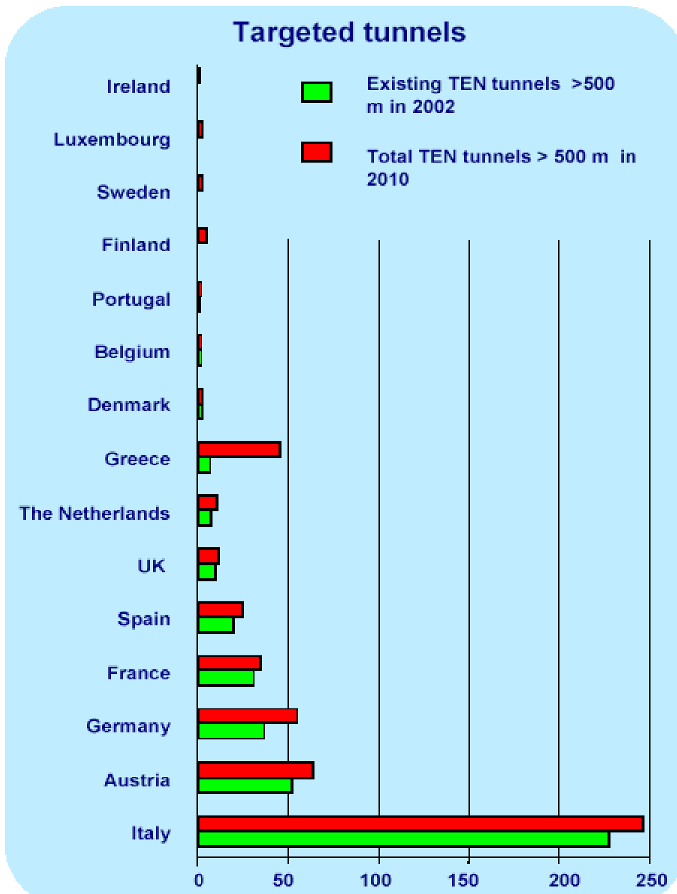


Figure 1.1: Distribution of tunnels longer than 500 m in EC member states (EC Memorandum, 2002).

The graph in Figure 1.1 shows the distribution of targeted tunnels between Member States. Several sources have been used to set up this inventory of both existing and future TEN road tunnels and notably the UN-ECE inventory of tunnels longer than 1000 meters. Tunnels between 500 and 1000 meters were identified primarily on the basis of Member States' statistics and other sources. To these tunnels the length of the tunnels of the new member countries, e.g. Bulgaria, Slovenia and Slovakia should be added. It is evident that the density of tunnels differs between European countries, what also means that road users from different countries are not equally acquainted with their use and proper behaviour in them. This could cause problem when users with different so called social traffic norms meet at the same place, in this case in tunnel, especially when due to enlargement of EC road travels will be more frequent.

What is of main concern for us in this report is the level of safety of tunnels. Based on the state of safety of tunnels and an identification of the main causes of accidents, relevant countermeasures will be suggested for increasing the safety level in tunnels. We understand the whole situation as a system in which the human factor is in interaction with traffic infrastructure. Of course the main emphasis will be on road users and their behaviour, but we must not forget that the behaviour is determined also by the whole traffic situation. Once again we should mention that there were less traffic accidents in tunnels than on open road, but when they were in the tunnel, it was more difficult to control events, even with smaller accidents (EuroTest 2002, see Figure 1.2)

Figure 1.2: Road tunnels checked in Eurotest 2002

In the Eurotest 2002 30 tunnels in Europe were tested for the tunnel system (e.g. number of tubes), conditions (e.g. lighting), traffic and traffic surveillance (e.g. one or two way traffic, congestion, and speed limits), communication (e.g. loudspeakers), escape and rescue routes, fire (e.g. fire protection equipment, alarm system), fire ventilation, and crisis management (e.g. regular fire drills). The rankings were calculated from a checklist of 8 categories with points allocated in each and weighted in importance, varying from “Very good” (at least 90 % of the total points) to “Very poor” (less than 60 % of the total points). The assessment of risk potential was based on the following factors: traffic volumes, proportion of heavy goods vehicles, tunnel gradients, one or two way traffic and traffic density and hazardous material on lorries. The German automobile club ADAC also performed tunnel tests within Europe (www.adac.de/Tests/Reisetests/Tunnel) over various years. The criteria they used were based on things like lighting, communication, emergency routes, fire protection, incident management etc. Also, the Dutch Automobile club ANWB (www.anwb.nl) performed tunnel tests in 2003. What we see in general from these tunnel tests is that the results are not very satisfactory. Especially weaknesses of the particular tunnel may give information about the problems that road users may have during emergency (e.g. no loudspeakers, too great distance between emergency exits, no rescue routes, emergency phones are not sound-proofed) or possibilities for accidents (e.g. no information on observing the minimum distance, no monitoring of speed limit). Data from these tunnel tests should concern us, because though rare events, possible accidents could develop in great disasters. Also a number of preventive measures should be undertaken, some of them connected to the behaviour of road users (e.g. speed and distance control).

1.4 Accidents in tunnels

The primary causes of accidents in *tunnels* can be classified into (Aty, 2002):

- *Internal causes* – mechanical or electrical failures concerning the control guide system as well as the logistic and in-service systems, i.e. events connected to malfunction of the tunnel hardware.
- *External causes* – earthquakes (Generally, tunnels have a fairly high safety against earthquakes), floods, avalanches, etc; efforts are being made to create software and hardware for crisis management, and extensive and efficient tunnel information management systems for use in response to accidents such as rock slide and earthquakes.
- *Causes associated to human action* – operating faults, errors during maintenance, sabotages, and terrorist attacks, and as we could add, before all, traffic accidents caused by improper behaviour of drivers.

With respect to this deliverable, especially category 3 is interesting, although all human response to accidents in tunnels (disregarding the official cause) are of primary interest.

Aty (2002) believes[1] that for many motorists tunnels are special facilities associated with a feeling of unease resulting from entering into the darkness combined with concern for one's personal safety. The driver may sense the strain in driving at night or in tunnels, since the visual environment is very different. The sense of enclosure and darkness in tunnels could causes drivers to feel less secure and become cautious. The drivers in excessively dense groups of vehicles thus seek to maintain a longer distance from the preceding vehicle at the entrance to the tunnels. This slows the vehicles down and the slowdown is propagated upstream in a wave of deceleration (Aty, 2002).

In a Norwegian study of 587 road tunnels (Amundsen and Ranes, 2000) in which 745 persons were killed or injured during the five-years period (1992-1996) it was found that the proportions of severely injured and killed in tunnel crashes were higher than the road crashes on the national road network. But average accident rates for tunnels were below accident rates assumed for two-lane roads in the Norwegian Roads and Road traffic plan (NVVP). This illustrates that tunnels are not crash prone but that accident severity is somewhat higher in tunnels than on the national road network in general. It was also found that improved lighting and tunnel entrance design have contributed positively to a significant reduction in tunnel transition zone accidents. However, there is still more room for additional tunnel entrance lighting improvements to tunnel traffic safety.
Analysis of the crash types showed that the proportions of frontal, single vehicle and other type crashes in tunnels were similar to those on road network as a whole. Rear-end collisions, however were twice as common in road tunnels as on the open roads. The distribution of tunnel and road crashes is shown in Table 1-1.

Table 1-1: Crashes in road tunnels and National roads by accident type in Norway (Amundsen and Ranes, 2000).

CRASH TYPE	INSIDE TUNNEL	NATIONAL ROADS OUTSIDE TUNNEL

[1] Regarding the fact that many drivers drive through tunnels without hesitation, we may doubt this belief. Perhaps it is valid for longer tunnels and/or for claustrophobic individuals or those that already (directly or vicariously) experienced an accident in tunel.

Same direction	43.3%	22.2%
Opposing directions	17.2%	14.3%
Crossing and turning	1.6%	23.7%
Pedestrian involved	1.6%	8.1%
Vehicle leaving road	29.8%	26.3%
Other accident types	6.5%	5.4%
Sum of accidents	**372**	**4917**

Crash rates decline with increasing tunnel length (Table 1-2). This is to be expected, as entrance zone crash rates are higher than those for the mid-zones. Also the crash frequencies in the entrance zones were higher for shorter than for longer tunnels. Narrow tunnels (smaller number of lanes) had higher crash rate than wider ones. It was found that there is a concentration of crashes outside tunnel openings on roads with one-way traffic. In such cases rear-end collisions predominate. These are often related to high traffic volumes and are sometimes exacerbated by blinding sunlight and closely spaced traffic signals (Aty, 2002; Amundsen and Ranes, 2000).

Table 1-2: Crash frequencies and rates and AADT (Amundsen and Ranes, 2000). Note that one might interpret the crash rate per mileage to decrease with increasing AADT. However, tunnels with a high AADT are normally better equipped (twin tubes) and therefore have a lower crash rate. More traffic in the same tunnel will NOT lead to a reduction of the crash rate.

AADT	Number of tunnels	Lengths (km)	AADT (average) (veh./day)	Travel (mill veh.km/yr)	Crashes	Crash rates (crash/mill veh.km)
0 – 500	108	83.7	400	11.3	13	0.23
501 - 1000	167	159.0	800	44.5	40	0.18
1001 - 5000	206	149.6	2,200	108.5	76	0.14
5001 - 10000	49	29.8	7,400	78.2	50	0.13
Over 10000	57	38	23,600	324.6	186	0.11
Sum	**587**	***460.1***	***4,000***	***567.1***	***365***	***0.13***

Aty (2002) quoted the results of the study of the signing in Boston's Central Artery (Interstate 93) tunnel. The low ceiling height and horizontal and vertical curvature within the tunnel reduce the distance from which the signs can be seen by motorists. Guide signs may be easily blocked from view by large trucks. Drivers, especially unfamiliar drivers, will have difficulty obtaining the guidance information they need to find the proper exit. This can lead to driver frustration and may also lead to a reduction of safety. Using a driving simulator helped in identifying potential solutions for the Central Artery Tunnel signing, which are as follows (after Aty, 2002):

1- Addition of initial interchange guide sign further upstream.
2- Use of interchange sequence signs to provide more advance notice to drivers of upcoming exits.
3- Relocation of guide signs to locations where they would be less obscured by tunnel walls or ceilings (due to horizontal or vertical geometry).
4- Redesign of guide signs to communicate information to the motorist more clearly.

Analyses of real accidents give invaluable data that are impossible to achieve through experiments and simulations. Such empirical information helps to keep approximations such as stage models and simulations realistic.

Voeltzel (2002) reported about actual behaviours 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 recognise the threat of the fire.

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, saving their life.

The victims of the Gotthard tunnel fire "died because of their false appreciation of the situation and their incorrect behaviour as they waited or tried to turn their vehicles, instead of proceeding immediately to emergency exits" (Report of the ad hoc Multidisciplinary Group etc., 2002).

From analyses of the Kings Cross fire in November 1997 Canter and 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. Passengers 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.

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.

Because tunnels are enclosed spaces, fires that occur result in poor visibility and the spread of smoke and toxic gases along the tunnel, the rapid development of high temperatures and a reduction in the level of oxygen in the air. The extent of harm to road users in the event of a fire in a tunnel is therefore far greater than on open roads. Therefore it is essential to provide adequate facilities for road users to escape or be rescued by emergency crews. This means that there should be enough escape routes and that the ventilation system needs to be fast and efficient, particularly in tunnels with bi-directional traffic. These prerequisites also apply in the event of an accident that does not involve fire, but which results in the release of toxic gases. Aty (2002) names 6 considerations in order to secure the safe operation of tunnels. Of those 6, the following are important to UPTUN WP3:

1. Spacing of the cross-passages that link the running tunnels to the service tunnel and form the escape routes for people caught in a fire (emergency escape routes need to be a point of attention in UPTUN as well).

2. Since the intervention time for rescue teams from the outside is very long (up to more than one hour), self-rescue is a priority. Personnel should be trained and have practice in the use of available fire-fighting equipment. In addition, all persons must have self-rescue equipment at their disposal[2].

[2] This is in our opinion not suitable for tunnel users. They should leave the tunnel in the case of emergency.

3. At the foot of the shaft and in other places, survival containers should be installed that have an independent emergency air supply. In emergency situations, these can guarantee survival until the end of fire or the arrival of external help.

4. It is very important that safety is provided to the tunnel users. It is recommended that the tunnel management authority should work out a proper safety management scheme. For example, every truck of enclosed structure should be inspected before entering a vehicular tunnel longer than a specified length. If necessary, all trucks of enclosed structure should be prohibited from using the vehicular tunnels during rush hours.

To achieve a better level of safety the primary objective is to prevent critical events and the secondary is to reduce the consequences. Basically, the driving rules that apply in tunnels are the same as those for open roads, i.e. maintaining a safe distance, observing speed limits and maximum loads, thoroughly securing all loads and warning other road users in the event of a breakdown or congestion. And even more so than on open roads, it is recommended that drivers listen to their radio while being in tunnels so that they are able to receive traffic reports as well as possible specific instructions. However, there are a number of additional traffic regulations that apply especially to tunnels (Aty, 2002):

- Overtaking is forbidden if there is only one lane in each direction
- No turning or reversing is allowed if not specifically asked for by tunnel officials
- Headlights must be used, even in lit tunnels
- No stopping is allowed in a tunnel, except in case of an emergency, in which case the engine must be switched off immediately.

1.5 Human Behaviour in building fires

1.5.1 Introduction

Research has demonstrated a remarkable consistency in people's behaviour during emergencies in an apparently wide variety of settings (Khoury, 2003; Canter, 1990; Canter, 1980-81; BRE, 1993; Bryan, 1998). People have reasons for being at particular places, and those reasons will guide their behaviour. This must be taken into account when considering what they might do in an emergency. The behaviour of people also depends upon the role they take. Much of the observed variation in behaviour can be accounted for by considering the role of the person carrying out the acts, and attempting to postulate rules which may be associated with those roles.

Three stages in people's emergency behaviour have been identified. The first of these has been called the interpretation stage. The ambiguity of potential disasters in their early stages, the rarity of such events and the tendency of people to interpret their surroundings in relation to the expectations of normal use, results in the initial cues being ignored or misinterpreted. People see what is going on around them and try to interpret and make sense of it. Their behaviour is then placed on or grounded in this interpretation. It is therefore essential to provide people with the necessary information, for them to be able to correctly interpret what is happening. Eventually the fire will be noticed, and behaviour then enters the second stage, where people decide what to do next. The information people receive is likely to be ambiguous and of limited use in their decision-making. Any additional information which can be given to people will make effective action more likely.

People differed greatly in relation to the number of cues necessary to alert them to the likelihood that something unusual was happening. The recognition of a single cue, such as smoke, was often followed by a search for other cues before people decide what is going on in and what they should do. In essence people are implicitly acting on the probability of cues being a consequence of a particular event. As emergencies are rare, such a probabilistic model is by definition likely to lead to a misinterpretation. This makes extra information to aid correct decision making of great importance.

The final stage is where people attempt to deal with the emergency, either by tackling the fire, interacting with other people, or escaping. One important aspect of this stage is that people are unlikely to produce acts under emergencies that they would or could not produce under normal circumstances.
For engineering purposes (BS7974) the 3 stages of behaviour are defined slightly differently, as Recognition, Response and Movement times. The Recognition stage directly matches the first stage described by Canter (1990), the Response stage however includes all actions other than movement to the exit, and thus overlaps somewhat with Canter's second stage. The Recognition and Response stages are often collectively referred to as "pre-movement time" although this is slightly misleading as movement may occur. The distinction is that the movement is not directed to evacuation, but to other activities.
Behaviour sequences appear to be a product of attempts to cope with the ambiguous, rapidly changing information. From case studies, a full and coherent account can be given for the sequences of actions without recourse to "panic" as a formal explanation.

1.5.2 Panic

Panic is a prominent concept when describing human behaviour during emergencies. Contradictory arguments and invalid assumptions continue to exist in references to panic in the newspapers, building regulations and academic literature. Panic is often used as a description, explanation or evaluation of a state of anxiety or pattern of "irrational" behaviour in a fire on the part of an individual, group or crowd (Sime, 1993, 1984). The anxiety or behaviour is assumed to be "irrational" since its outcome is likely to be unfortunate (crowd crushes at exits, failure to move away from smoke, etc). When it comes to crowd behaviour during emergencies much has been written about the tendencies for panic. During the first half of the 19th 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 problem; 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".

This definition has been questioned in various articles. E.g. Sime (1995) 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. In other words, panic is the result of other problems rather than the source of problems. Summarising 50 years of research, Quarantelli (1999) comes to similar conclusions.

Anxiety-prone people may spend up to 40% of their time in "irrelevant" actions (Proulx, 1993). Unfortunately, the primary criterion adopted for panic or irrationality is the inappropriateness of behaviour as judged from someone else's perspective. Behaviour in fire can only be properly judged against the individual's awareness of options available at different stages, his familiarity with the building and the general constraints of the fire situation.

The kind of flight behaviour described retrospectively as panic, may eventually be necessary if people are to have any chance of escape. People may be forced into a position where they are unable to act immediately or on their own initiative, because their awareness of a potential danger is delayed and the options available are thereby reduced until it is too late. "When people, attempting to escape from a burning building pile up at a single exit, their behaviour appears highly irrational to someone who learns after the panic that other exit were available. To the actor in the situation who does not recognise the existence of these alternatives, attempting to fight his way to the only exit available may seem a very logical choice as opposed a burning to death" (Turner & Killian, 1957). Until fairly recently, the stereotype image of panic as a reaction to disaster led to delays in giving warnings, and ambiguous messages. The strategy of limiting the information available to people in a fire in the early stages as previously advocated in the building regulations and design literature has now been abandoned, fortunately.

In general, a retrospective allusion to the lack or misuse of safety facilities in a fire "because people panic", reflects the way in which the concept of panic is used. It is less likely to provide an adequate explanation of people's behaviour and fire.

1.5.3 Stage 1: Recognition Time

The time taken for individuals to recognise the existence of a fire is a complex function of many parameters. Some of these refer to the individual, their degree of alertness, the extent to which they are committed to their current course of action. The information content of the cues reaching them is also of great significance. The complexity of the building environment may affect whether any direct visual cues will be received. The means of raising the alarm also carries varying degrees of information.
"The most important finding of the research is the fact that the start up time (i.e. peoples reaction to an alarm) is as (if not more) important as the time it takes physically to reach an exit. ... On average two-thirds of the time from onset of the alarm to reaching an exit was spent by people not moving at all. On average one-third of the time was spent in moving from seat positions to an exit" (Sime, 1992)
BS7974 has defined four classes of warning system:

W0 -	no system in place
W1 -	siren or bell
W2 -	pre-recorded or standard voice announcements
W3 -	public address linked with CCTV so that announcer can see the occupants, and direct messages to individuals as appropriate. Alternatively, members of staff on the scene to directly interact with building occupants.

For occupants familiar with the building and its procedures (e.g. office staff), a W1 class system may be just as effective at promoting an early response as a W2 or W3 system. However if the occupants are unfamiliar, it is quite likely that bells and sirens will simply be ignored until other supplementary cues become available.

A number of researchers (Pigott, 1988, 1993; Bellamy, 1989; Proulx & Sime, 1991) have studied the effectiveness of informative fire warnings (i.e. that specifically mention fire, and which may also direct people to appropriate exits). Proulx and 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 on the platform. They knew that there was 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 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 PAs 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 PAs from the Control Room.

5. The control room in full operation issuing directive PAs. No staff members present on the station. The PAs 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 simple and brief information speeds up 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.

Estimates of likely Recognition Times for different types of buildings, with different warning systems W0…W3 have also been made (Purser, 1998). The various factors that influence the recognition time have been incorporated into an Occupant Response Escape Time (ORET) model (Sime, 1984, 1996, 1998). A simplified occupant response time model has been proposed for road tunnels (Ashe & Hall, 1999) that takes a basic response time depending on the type of warning, and then modifies this according to other input parameters such as occupant characteristics, way finding, hazard identification and basic response time.

In crowds, communication is slower and more difficult. This is even worse if technology for mass address is not present, operable or adequate; there is also the possibility that noise generated by large numbers of people may mask any public address. During the process of evaluating cues, a person is very perceptive to the overt actions and communications of others, and may choose to mimic these rather than react independently (Bryan, 1988). Although the activities of other people are potentially important, they may also easily be misinterpreted (Canter, Donald & Chalk, 1995). Separated individuals respond rapidly but family groups wait until clear sign of fire threat. However, if there are many people witnessing any event they may all tend to assume that it is "someone else's problem".
Members of the public differed greatly in relation to the number of cues necessary to alert them to the likelihood that something unusual was happening. The recognition of a single cue, such as smoke, was often followed by a search for other cues before people decide what is going on in and what they should do.

1.5.4 Stage 2: Response Time, Non-egress behaviours

Tong and Canter (1985) noted that people who were familiar with a building tended to leave later, choosing to do other things first. To some extent their familiarity is likely to be coupled with their role in the building; this role may have responsibilities which require various actions to be performed. Also, a person familiar with the building will confidently make accurate estimates of the time it will take them to get out. However, the rate of fire growth is consistently underestimated, with the overestimate of time between stages as much as two minutes as fire gets large. If the person delays evacuation until they think they can just get out before untenable conditions occur, they may be too late. An unfamiliar person would leave earlier to allow a larger safety margin to account for their uncertain estimate of the time required.

Group Behaviour

The behaviour of family members in the Summerland fire, 1977, was altruistic and group oriented. Deaths were statistically most likely to occur amongst people trying who were in groups when first alerted. This was evidently because people already in groups started to move later than individuals separated from other group members, and move more slowly as a group. An initially intact group was more likely to regroup after dispersing, and pass through the main exit in their interact group. At least three-quarters of the people interviewed escaped with at least one other group member.
The fact that people often (and indeed normally) move in groups, rather than a mass of individuals, is still not represented in engineering models of crowd movement. Human cognition, decision-making and behaviour will need as close attention as human movement and hazard growth predictions, if the simulations are to validly represent the time it would take people to escape in reality (Sime, 1993).
A study of high-rise building evacuation drills (Proulx, 1995) found that carrying babies did not significantly slow people down (0.22 - 0.77 m/s on stairs). Small children (aged 2-5) and elderly 0.45m/s on stairs. People tended to form groups of 2-3 (family/neighbours) and move at speed of slowest. When a group leader's actions turn out to be unsuccessful, the group may split and / or follow a new leader (Jones & Hewitt, 1985).

Co-operative / Altruistic Behaviour

The co-operative nature of actions in the work environment was often a feature, tasks being allocated and undertaken, assistance to workmates rendered and people being generally helpful. This type of behaviour is repeated in dwellings, albeit on a smaller scale (Canter, 1990; Wood, 1972). Other studies also found altruism was common (Bryan, 1988).

Fire-fighting

The popularity of fire fighting as a course of action was unexpected, accounting for almost 25% of the first actions taken in factories compared to only 10% in dwellings It would seem likely that there is some threshold value of "fire severity", as judged by a person, beyond which a person would call the fire brigade. This may vary from different people, depending on page, sex, presence of others and other individual differences. Below this threshold, people would fight the fire as they judged they had a reasonable chance of success.

Movement in(to) Smoke

There was a surprisingly large percentage of people moving in smoke, an action which was previously believed to be fairly rare. Wood's research (Canter, 1990; Wood, 1972) demonstrated that moving in smoke is not associated with leaving the building, nor with knowledge of emergency exits, and he could only assume that it is undertaken while performing some other activity, such as fire fighting or warning others. Further research showed that people would move through smoke to reach an exit; this was more likely if they knew the building geometry and could estimate how long it would take even though they could not see their destination (Bryan, 1988). Secondary variables were perceived severity, smoke density, and presence of heat. Over 80% of people move at least as far as the visibility distance, nearly 50% exceed visibility distance. Fewer than 3% turn back when visibility > 10m, 6% 4-10m, 24% 2-4m, 37% 1-2m, rest <1m.

The World Trade Centre evacuation in 1993 included movement in smoke, and very long evacuation times (Fahy & Proulx, 1995). Although the smoke was very dilute, the complete darkness due to failure of the emergency lights must have made the situation seem much worse to the evacuees. However they continued to move rather than seek refuges in most cases; the fear of being trapped in such an exceptionally tall building with little hope of rescue may well have been a factor.

Building Re-entry

The high percentage of people who return to the building highlights the difficulty many people experience in apparently "doing nothing" when their possessions and property are threatened. A certain proportion of people seem motivated to return to "check the progress of the fire" if they do not actually do anything about it. If a certain percentage of people will return into the building for apparently not very rational reasons, then perhaps a similar percentage will wish to leave a "safe area" within the building, rather than remain passive and inactive.
The Arundel Park fire (1951 - a church-sponsored 'oyster roast' for families) was the first incident where re-entry was studied in depth (Bryan, 1988): about 33% of the people (mainly male) re-entered. Re-entry mainly applies to residential buildings.

Conclusion

"What we are really lacking, and more obviously follows from this research is some attempt to gain insight into the decision process which leads to certain course of action. In the present research we have simply asked people what they did, without reference to what other courses of action were considered and rejected. We cannot hope to make predictions about behaviour, if we do not have some evidence as to why people did one thing rather than another". - PG Wood (Canter, 1990).

Many papers on human behaviour merely list the actions that have been performed, possibly with statistics to indicate the popularity of various options. There is no attempt to make sense of the data by organising the actions into sequences. However there are a few examples of the way behavioural data should be collected and presented (Saunders, 1996) although a recent paper (Boyce, Fraser-Mitchell & Shields, 1998) only dealt with a drill rather that a real incident. The action sequences were assumed to occur after the preceding action had been completed, rather than changed in response to circumstances.

1.5.5 Stage 3: Egress Time, Movement

Much effort has gone into measurements connected with the movement stage of evacuation, although it is now appreciated that this stage may not be the main determinant of the overall evacuation time.

Unimpeded walking speed

The movement speed of "able-bodied" individuals varies widely. However there seems to be reasonable agreement regarding an "average" value. This is shown in Table 1-3 below.

Table 1-3: Average values of movement speed according to various sources.

Speed	Reference
0.8m/s (elderly woman) 1.7m/s (young adult male) 1.4m/s (mean value)	[Ando et al, 1988]
0.97m/s	[Predtechenskii & Milinskii, 1978]
1.25m/s	[Pauls, 1987]
1.3m/s	[Polus et al, 1983]
1.4m/s	[Older, 1964]
1.2m/s	[Nelson & MacLennan, 1988]

Many observations have shown that the unimpeded speed distribution curves are (approximately) normal (Still, 2000). Disabled people do not necessarily move more slowly than able-bodied people on a flat surface (Boyce, Shields & Silcock, 19991, 1999b; Shields & Boyce, 1995; Pearson & Joost, 1983) but inclines are more challenging, and stairs may be impossible without assistance. Ramp slopes should be less than 1 in 15 for wheelchair access Lischer, 1993).

In the USA, the production of the Americans with Disabilities Act included studies of disabled egress times. This work concluded that average disabled egress velocities were 27 m/min, with a requirement to rest for 2 minutes every 30 metres. "This gives an average velocity of 9.7 m/min per 3.11 minute interval." (0.15 m/s). This figure needs to be considered in relationship to the average walking velocity of unimpeded persons of at least 72 m/min. (1.2 m/s)
Some other speeds - to provide a sense of scale (http://www.civil.canterbury.ac.nz/sfpe/newsletters/45s1-1.shtml):

Running, 100 m world record	600 m/min	10 m/s
Running, jog	300 m/min	5 m/s
Running, wet floors	130 m/min	2.1 m/s
Running, up stairs	33 - 68 m/min	0.5 ~ 1.1 m/s
Walking, fast	120 m/min	2 m/s
Walking, slow	50 m/min	0.8m/s
Walking, upstairs, (slope speed)	31 m/min	0.5 m/s
Walking, darkness, unknown	18 m/min	0.3 m/s
Walking, fire design purposes	14 m/min	0.25 m/s
Wading, knee deep	43 m/min	0.7 m/s
Wading, waist deep	18 m/min	0.3 m/s
Handicapped, fast walk	20 m/min	0.33 m/s
Handicapped, slow walk	10 m/min	0.17 m/s

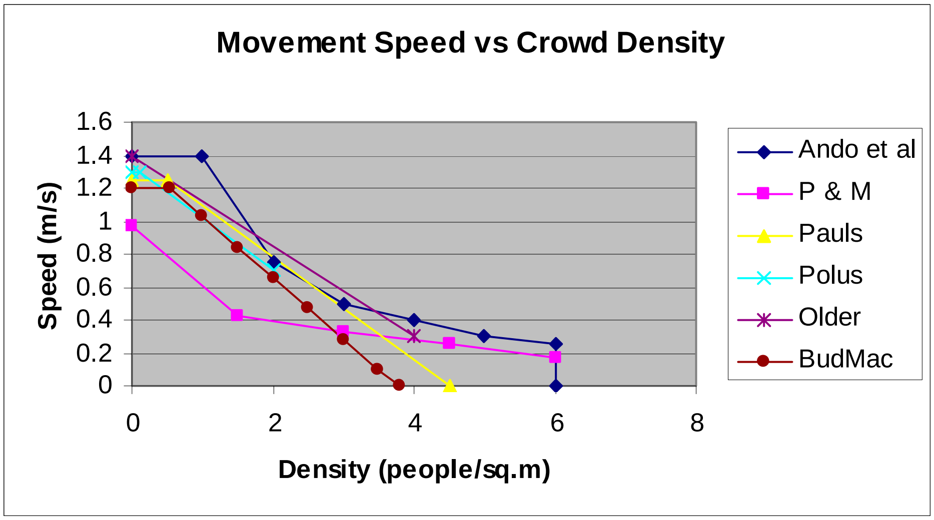
Effect of Crowd Density

Predtechenskii and Milinskii (1978) calculate densities from projected area (Kendik, 1985), where a child occupies between 0.04 ~ 0.06 m^2, a teenager 0.06 ~ 0.09 m^2, adult 0.10 ~ 0.125 m^2 (depending on coats), 0.18 m^2 (carrying briefcase), 0.24 m^2 (carrying one suitcase) or 0.39 m^2 (carrying two suitcases). Fruin has a 'no touch' zone of 0.28 m^2 (up to 0.68 m^2) as long as movement within the queuing area is not necessary (Kendik, 1984).

Crowd density is more commonly expressed in terms of people per square metre, rather than fractional projected area. A body size of 0.133m^2 is implied in Simulex (Thompson & Marchant, 1993) (converting the Predtechenskii & Milinskii speed-density relationship to the more usual density expressed in people per square metre). Predtechenskii & Milinskii have a maximum crowd density of 32people/4.2m^2, ie 7.6 people per square metre. A body size of 0.135m^2 allows a density of 7.4 people per square metre. In London Underground carriages, a typical body ellipse is 450mm x 600mm, hence 4.7 people per square metre. Up to 5.4 people per square metre is considered 'safe' for stationary crowd (Dickson, 1993).

It is speculated that the speed/density relationship should be a function of the individual unimpeded speed (Still, 2000).

The same sources quoted in the table of unimpeded movement speed also give speed-density relationships. These are summarised in the following figure.



Movement on Stairs

Some sources quote values as a function of the width of the stair: 1.1 people/m/s (going up), 1.15 people/m/s (going down) (Melinek & Booth, 1975; Malhotra, 1984). (Pauls (1987) noted Melinek & Booth confused between peak and mean flows, also actual and effective width.).
More commonly, speed of movement is related to crowd density, as for movement on horizontal surfaces. Note that speed may be measured along the slope, split into components, or in some cases not made clear.

Speed	Reference
On stairs speed 1.1m/s along slope (0.9m/s horizontal component,0.6m/s vertical). Optimum flow rates occur for density ~ 2 people/m^2, speed 0.5 m/s.	[Pauls, 1987]
Unimpeded speed on stairs 0.75 m/s (cf Fruin horizontal component 0.7m/s), in crowded conditions 0.5 m/s. An EVAC chair for the disabled went 0,62 m/s. Disabled usually wait in refuge until able-bodied have gone.	[Rubadiri & Roberts, 1994]
Speeds on stairs 0.52, 0.54, 0.62 m/s. Carrying babies did not significantly slow people down (0.22 - 0.77 m/s on stairs) Small children (2-5) and elderly 0.45m/s on stairs.	[Proulx, 1995]
1.0 - 1.23 m/s for stairs of varying slope. Speeds are along the line of travel, so must separate into components for slopes such as stairs.	[Nelson & MacLennan, 1988]

Disabled people may achieve very different movement speeds, need to stop and rest far more frequently, or possibly not be able to negotiate stairs at all without assistance (Boyce, Shields & Silcock, 1999b).

Movement in Corridors

Movement in corridors is basically controlled by the speed of movement on horizontal surfaces. Above a minimum width of about 4 feet (1.2m), the flow rate of people was found to be directly proportional to the corridor width (Hankin & Wright, 1958). If people have a crowd density d people/m^2, and are moving with a speed s m/s, the flow rate per metre width of corridor is given by R = s.d people/m/s. As the density increases, the speed decreases, so the flow rate is fairly constant. Melinek and Booth (Malhotra, 1984; Melinek & Booth, 1975) observed a rate of 1.5 people/m/s. To account for the effect of fairly narrow corridors, an "effective width" model has been proposed (Pauls, 1988; Nelson & MacLennan, 1988).The actual width is reduced by 0.2m corridor/ramp walls, up to 0.46m in wide concourse / passages. The true width of the passage is used when calculating the crowd density, the effective width w* gives the flow rate: F = R.w* people/s.

Flow rates through doors

Numerous measurements have been made of the flow rates of people through doors, since this is often a determining factor for the overall evacuation time.

Flow rate	Reference
1.5 people/m/s	[Aqua Group] *Aqua Group (1994)*
1.7 ~ 2.0 people/m/s ~1.3 people/m/s 1.33 people/m/s	[Melinek & Booth] [British Standards (1968/1971) [French Building Code] *all described in Melinek & Booth (1975)*
0.9 people/m/s. 1.04 ~ 1.57 people/m/s	[Home Office guide] [BS5588 Pt.3, Building Regs 1991 AD 'B'] *both described in Hodgson (1993)*
0.42 people/s 1.33 people/m/s 1.4 people/m/s 1.2 people/m/s 1.82people/m/s peak rate	[London Transport turnstiles] *described in London Transport, 1989* [BS5588 pt. 2,6,10] *British standards Institute, 1989-1991* [observed at football match] *Poyner et al (1972)* [Green Guide] *Institution of Structural Engineers (1989)* [Green Guide] *Home Office (1990)*

UK regulations (Hogson, 1993) are based on a 2.5 min escape time (which dates back to Empire Palace Theatre fire in 1911) - resulting in the figure of 40 people/min/unit width. Home Office guidance sets unit width at 0.75m, BS5588 Pt.3 and Building Regulations 1991 AD 'B' both specify a minimum width of 800mm for 50 people but allow reduction to 0.53m unit width in some circumstances. There are different means of defining door width (none of which correspond to 'effective width' as defined by Pauls (1988) and Nelson & MacLennan (1988))

The number of doors provided (for public assembly areas) should be such that the notional evacuation time does not exceed 7~8 minutes, otherwise people become restless (Dickson, 1993; Stanton & Wanless, 1993). Disabled people may experience more difficulty in negotiating doors and other gaps; in some cases they may lack the strength or dexterity to even open a door (Boyce, Shields & Silcock, 1999c).

Movement in Smoke and other factors

Jin and Yamada define light extinction coefficient C (units 1/m) by

$$C = -\ln(I/Io) / L$$

where I is the transmitted light intensity, Io the initial light intensity, and L is the light path length (m). The light extinction coefficient is related to optical density D by C = 2.3 D.

For smoke where $C<0.3m^{-1}$ there is little effect, normal speed is 1.2m/s. Non-irritant smoke reduces speed to 0.3m/s when $C \sim 1.2\ m^{-1}$; irritant smoke reduces speed to 0.3m/s when $C = 0.5\ m^{-1}$. (Blindfolded people move at 0.3m/s) (Jin & Yamada, 1985).

The limit to what most people will endure (Jenssen, 1993a) is irritant smoke at OD 1.53 - 2.26/m, exposure 3-4 minutes, escape path 25-30m, speeds 0.2-0.5m/s. Those who survive moving in smoke travel an average distance of 9.1m; only 10% go further than 16m.
Point sources of light are impractical for wayfinding when smoke optical density exceeds $1.5m^{-1}$, corresponding to a visibility distance of 0.6m to outstretched hand for example. A notched rail is far more effective as a guidance system in dense smoke (Jenssen, 1993b). Blind people can move as quickly as sighted.

A wind speed of 5m/s (cf. current guidance limit of 3m/s) does not significantly affect movement through exits (Home Office, 1993). This has relevance to smoke control systems using fans which draw their replacement air through the doors. This could also be relevant to tunnel ventilation systems.

Wayfinding & Exit Choice

Anecdotal evidence abounds for people's preference for a familiar route, but there has been very little research to quantify this. In an IKEA store, it was shown that shoppers would walk twice as far to use a familiar exit compared to an unfamiliar one (Benthorn & Frantzich, 1998).
If people are familiar with the building, they will exploit short cuts to get to their destination (Still, 2000) (ie. all routes are "familiar"). Thus members of staff leave by fire exits, visitors by the main entrance (Tong & Canter, 1985). Given a choice of routes, 80% of people prefer using ramps to staircases Mandetta, 1993).

The tendency of people to stick to the routes they know may be overcome to some extent by the provision of guidance systems (eg signs). Floor plans ("you are here") can increase movement time because people try to memorise them. Good direction signs on the other hand speed up evacuation (Groner, 1993). Of course, some disabled people may not be able to see / read the signs (Boyce, Shields & Silcock, 1999d).

1.5.6 Physiological Impacts of Smoke

A number of different models (Purser, 1988, 1989; Bryan, 1986; New ASTM standard, 1995; Lieberman et al, 1994) have been proposed to account for the impact of various toxic gases on humans. Most are based on the concept of Fractional Effective Dose, where the dose rate is a function of various species concentrations, and is integrated over the duration of the exposure. When the accumulated FED becomes equal to 1.0, the exposed person is assumed to be unconscious / dead at that point. For design calculations, the dose rate is assumed to be dependent only on the environmental conditions, but in fact the variation in uptake rate between different people (e.g. an elderly asthmatic, or a young fit adult) may vary by a factor of 10 or so (Zhao, 1998; Hartzell, 1998). The effect of FED<1.0 is on a person's performance is also not well understood.

As well as gases, the effect of exposure to heat has also been handled by a FED approach. Usually this is limited to convective heat transfer, when a person is immersed in / breathing hot smoke. Radiative heat transfer is handled by setting a threshold radiation flux, above which a region of the building becomes untenable due to rapid skin pain. However a FED approach for radiation has also been suggested (Clements & Gillespie, 1995), based on the time for skin pain to occur as a function of incident radiation flux. If for example the flux level is such that skin pain would occur in 50 seconds, then the FED rate is 1/50 =0.02 per second.

Flux	pain time	FED per second

(kW/sq.m)	(s)	(1/s)
25	1	1
15	2	0.5
11	3	0.33
8	5	0.2
4.7	10	0.1
3.5	15	0.067
2.8	20	0.05
2.5	25	0.04
2.3	30	0.033
2.15	40	0.025
2.07	50	0.02
2	60	0.0167
1.9	70	0.0143
1.8	80	0.0125
1.7	infinite	0

1.6 Human Behaviour in Tunnel Fires

1.6.1 Recent Tunnel Fires

There has been a spate of serious tunnel fires in recent years. The website of the “Fire in Tunnels (FiT)” network (www.etnfit.net) lists most of these, with brief details. However there are few accounts of these fires in the published scientific literature, and fewer still that discuss human behaviour in any depth. The approach adopted in this section has therefore primarily involved a search of the internet for news articles, particularly those with witness statements that shed some light on what people were doing. Clearly this will only give at best a qualitative description of behaviour; it will not be possible to estimate the probabilities of different actions being performed.

Table 1-4 lists the tunnel fires that were surveyed in this review.

Table 1-4: List of all reviewed tunnel fires.

Date	**Tunnel**	**Type**	**Dead**
18/02/03	Taegu, S. Korea times.hankooki.com/lpage/nation/200302/kt2003022418560411970.htm www.cnn.com/2003/WORLD/asiapcf/east/02/18/skorea.fire/ www.cnn.com/2003/WORLD/asiapcf/east/02/23/skorea.subway.charges/ english.chosun.com/w21data/html/news/200302/200302250029.html www.asahi.com/english/op-ed/K2003022000330.html quickstart.clari.net/qs_se/webnews/wed/ak/Qskorea-fire-arrest.R6un_DFO.html taipeitimes.com/News/front/archives/2003/02/20/195214 www.townmax.com/community/announcement/an_list.asp?sid=440 www.firetimes.com/subcontent.asp?FragID=7757 www.time.com/time/asia/magazine/article/0,13673,501030310-428127,00.html uk.news.yahoo.com/030218/80/dtioo.html www.guardian.co.uk/korea/article/0,2763,897925,00.html quickstart.clari.net/qs_se/webnews/wed/at/Askorea-subway-fire.RCer_DFN.html times.hankooki.com/lpage/200302/kt2003021821164510440.htm	Metro	197(+)

	english.chosun.com/w21data/html/news/200302/200302190026.html www.china.org.cn/english/international/56280.htm www.theage.com.au/articles/2003/02/19/1045638358948.html		
25/01/03	Chancery Lane, London Underground, England news.bbc.co.uk/1/hi/England/2694503.stm	Metro	
03/11/02	Homer Tunnel, New Zealand onenews.nzoom.com/onenews_detail/0,1227,144653-1-7,00.html onenews.nzoom.com/onenews_detail/0,1227,143887-1-7,00.html onenews.nzoom.com/onenews_detail/0,1227,143633-1-7,00.html	Road	
20/02/02	Cairo, Egypt www.emergency.com/firepage.htm	(Rail)	243
24/10/01	St Gotthard, Switzerland fpeng.peopledaily.com.cn/200110/25/eng20011025_83124.html www.guardian.co.uk/international/story/0,3604,580344,00.html www.t-e.nu/Publications/Bulletin/T&EBull103.pdf www.dawn.com/2001/10/25/int10.htm www.guardian.co.uk/international/story/0,3604,581224,00.html www.guardian.co.uk/international/story/0,3604,580344,00.html www.cnn.com/2001/WORLD/europe/12/21/tunnel.reopen/?related archives.tcm.ie/breakingnews/2001/10/25/story27708.asp www.construction.com/NewsCenter/Headlines/ENR/20011031b.asp edition.cnn.com/2001/WORLD/europe/10/25/switzerland.tunnel/ www.telegraph.co.uk/news/main.jhtml?xml=/news/2001/10/25/wtunn25.xml	Road	11
06/08/01	Gleinalm, Austria edition.cnn.com/2001/WORLD/europe/08/06/austria.fire/ news.bbc.co.uk/1/hi/world/europe/1476385.stm www.mathematik.uni-ulm.de/de-news/2001/08/062000.html#3 www.cnn.com/2001/WORLD/europe/08/06/austria.fire/	Road	5
18/07/01	Baltimore (Howard Street), USA www.tompaine.com/feature.cfm/ID/5878 www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6793 www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/13754.html	Rail	
11/07/01	Schiphol, Holland News.airwise.com/stories/2001/07/994858669.html	Rail	
27/11/00	Laerdal, Norway www.aftenposten.no/english/local/d176816.htm www.bergen-guide.com/538.htm www.iht.com/cgi-bin/generic.cgi?template=articleprint.tmplh &ArticleId=2697, International Herald Tribune, 7 Dec 2000.	Road	
11/11/00	Kaprun, Austria danger-ahead.railfan.net/reports/rep2000/kaprun20001111_04.html news.bbc.co.uk/1/hi/world/europe/1528917.stm www.funimag.com/funimag18/Funimag-Kaprun03.htm, Interview of Manfred Müller (technical director of the "Kapruner Gletscherbahn") in the Stuttgarter Nachrichten, November 14th 2000 www.skitastic.com/latest/news/111100.html europeforvisitors.com/switzaustria/articles/kaprun_gletscherbahn_fire.htm www.natives.co.uk/news/1100/12kaprun.htm	Rail	158

	ski.mountainzone.com/2001/news/html/111400.html www.wsws.org/articles/2000/nov2000/aust-n16.shtml Petrovitsch, H (2000), Disaster on Austrian Funicular, Today's railways, No 61 (2000), page 6 The Observer newspaper, travel supplements, 28th January 2001		
29/05/00	Cross Harbour Tunnel, Hong Kong Legislative Council Panel on Transport, Fire Incident at the Cross Harbour Tunnel on 29 May 2000, Hong Kong	Road	
29/05/99	Tauern, Austria news.bbc.co.uk/1/hi/world/europe/355940.stm www.guardian.co.uk/Archive/Article/0,4273,4284634,00.html www.landroverclub.net/Club/HTML/Travel_TauerTunnel.htm www.firehouse.com/news/99/5/30_APtunnel.html The Guardian newspaper May 31st, 1999 The Observer newspaper, 30th May 1999 Peter, F (2004) Causes, effects and control of real tunnel fires	Road	12
24/03/99	Mt Blanc, France/Italy news.bbc.co.uk/1/hi/world/europe/304219.stm www.mrtunnel.com/page3.htm The Guardian newspaper, March 27th 1999 The Guardian newspaper, third of April 1999 The Observer newspaper, 28th of March 1999, Mont Blanc tunnel fire investigation, Tunnel management international magazine, June 1999, p.6 Fire Prevention, 320, May 1999 page 8 Shipp, M, private communication (e-mail dated 3rd of May 2001) New Civil Engineer, 1-8 April 1999 Fire and flammability bulletin, May 1999 Peter, F (2004) Causes, effects and control of real tunnel fires	Road	39
10/07/98	Guizhou, China scout.wisc.edu/addserv/net-news/98-07/98-07-29/0001.html	Rail	80+
18/11/96	Channel Tunnel, England/France www.ntsb.gov/ITSA/channel_tunnel_fire_exposes_safe.htm, Journal of Commerce, May 14, 1997 www.writer-tech.com/pages/summaries/summchunnel.htm , Comeau, E, English Channel Tunnel Fire, November 18, 1996, NFPA Report www.railways.dft.gov.uk/ctsa/18nov96/chap3.htm www.railways.dft.gov.uk/ctsa/18nov96/chap8.htm www.railways.dft.gov.uk/ctsa/18nov96/chap9.htm#9h www.emergency.com/chunnel1.htm Berman, J & Ody, K (1995), Human factors and emergency response: the assessment of an integrated system, 2nd TUNNEL SAFETY CONFERENCE, p.173-180.	Rail	
18/03/96	Palermo, Italy www.medbc.com/annals/review/vol_10/num_4/text/vol10n4p233.htm pdm.medicine.wisc.edu/Masellisa.htm	Road	5
28/10/95	Baku, Azerbaijan	Metro	289

	www.azer.com/aiweb/categories/magazine/34_folder/34_articles/34_metro.html, Azerbaijan International (3.4) Winter 1995 home.no.net/lotsberg/artiklar/andersen/en_table_1.html www.mndaily.com/daily/1995/10/30/world_nation/wn30aa.ap/		
15/10/94	Kingsway (Mersey) Tunnel, England Gillard, J & Arch, P, (1995) Mersey Tunnels Kingsway Tunnel fire incident 15 October 1994, 2nd TUNNEL SAFETY CONFERENCE, p.97-106	Road	
01/03/94	Huguenot Tunnel, South Africa Gray, D & Varkevisser, J, (1995) The Huguenot Toll Tunnel Fire, 2nd TUNNEL SAFETY CONFERENCE, p.57-66	Road	1
19/02/91	Bethnal Green, London Underground, England Rose, J & Harding, B, Monitoring, analysis and management of safe operations in a high-capacity tunnel Metro, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, 1993, p.351-359	Metro	
16/01/91	Zurich, Switzerland Fermaud, C, Jenne, P & Muller, W, (1995) Fire in a commuter train – rescue procedures as perceived by passengers, 2nd TUNNEL SAFETY CONFERENCE, p.181-188	Metro	
18/11/87	Kings Cross, London Underground, England www.firetactics.com/KINGSCROSS.htm Canter, Donald & Chalk, 1995	Metro	31
20/12/84	Summit Tunnel, England www.fireservice.co.uk/summit.php Lindley, J, (1997) The Summit Tunnel Incident, I.Chem.E. Loss Prevention Bulletin 134	Rail	
02/11/82	Salang Tunnel, Afghanistan www.fis.edu/eslweb/esl/students/projects/disaster/salang.htm, see also Smith, R, Catastrophes and Disasters, pub. New York: Chambers 1992 quickstart.clari.net/qs_se/webnews/wed/ba/Qafghan-tunnel.RZ-I_DFK.html	Road	400+
17/01/79	San Francisco BART, USA Chan, R & McCleery, J (1995) Human Factors, 2nd TUNNEL SAFETY CONFERENCE, p.163-172	Metro	1
01/08/70	New York, USA www.nycsubway.org/faq/accidents.html	Metro	1

1.6.2 The Fire Environment

The behaviour of people will be strongly influenced by their environment. It is therefore appropriate to briefly consider the likely nature of the conditions that will be experienced, before going on to describe the observed behaviour.

Rapid Fire Growth

Rapid fire growth and / or smoke spread has been a common feature to many of the tunnel fire incidents examined in this review. Due to the nature of the fire load, fires were also likely to sustain a high intensity for a considerable duration.
Rapid fire growth may be due to the use of aging stock and flammable materials / finish. In the Baku Metro fire, flammable materials accounted for 90% of the finish of the cars, manufactured in the late 1960's. The Taegu Metro fire was arson, started by a small quantity of accelerant. However the seats and linoleum floor of the train were highly flammable. The platform security camera showed the first train clearly alight within 1 minute of ignition (the arsonist was also observed on camera). The suspect had a history of mental illness, and was reportedly attempting to commit suicide.

Leaking hydraulic oil from a cable trickled into the heater and the surrounding area on the Kaprun funicular railcar, where it then ignited. The car was fairly modern (1994), and supposedly made from fire-resistant materials, but after the fire only the metal base of the train remained.

Road vehicles may also be capable of producing a rapidly-growing fire. In an analysis of tunnel fires in the Nice region of France, 98% of lorry fires start from the rear wheel axle, as a result of using brakes too much on steep gradients; tyres ignite at about 300 to 400 degrees centigrade. These rear wheel axle fires have a fairly slow fire development. However, the remaining 2 percent of fires occur in the engine compartment, and have very rapid growth with serious potential consequences.

The fire in the Huguenot tunnel was exacerbated when the main diesel tank of the crashed bus exploded. The fire initially started in the engine compartment while the bus was moving.
Fuel may be spilt in road tunnels following collisions and crashes. In the St Gotthard tunnel two trucks, one carrying tyres and tarpaulins, collided. Survivors and rescue workers described how litres of petrol from the crumpled trucks then washed over the tunnel floor, causing a huge explosion to rip through the structure and starting a fire which blazed throughout the night.

Spilt petrol was also responsible for the initial rapid growth of fire in the Tauern tunnel. A lorry carrying paint was one of the vehicles involved in the crash that started the fire. Several explosions followed, probably spray cans exploding and flying around burning, spreading the fire to other vehicles.

Highly flammable cargos were involved in a number of other fires in tunnels. Hazardous cargo including highly flammable chemicals was involved in the Howard Street Tunnel Fire, Baltimore. A petrol freight train derailed at 40 mph in the Summit Tunnel, leading to an explosion and subsequent intense fire. In a tunnel along the Palermo-Punta Raisi motorway, a road accident occurred involving a tanker-truck loaded with 8,000 litres of liquid petroleum gas. The tanker was hit by a motor-coach that tore open the upper part of the tank, releasing gas that ignited in a few seconds. The flames overheated the LPG remaining in the tanker causing a BLEVE (Boiling Liquid Expanding Vapour Explosion). Fortunately, the time interval between the ignition of the gas and the explosion enabled a number of people to escape from the 150m-long tunnel.

What happened inside the Salang tunnel in 1982 is unclear, but some reports claim that the accident was caused by an Afghani driving a fuel tanker on a suicide mission, who deliberately crashed into the line of Russian military vehicles.

The Mont Blanc tunnel fire broke out on board a Belgian-registered food truck carrying flour and margarine through the tunnel. The flames were possibly caused by fuel dripping onto the hot exhaust pipe which came from under the cabin. "Everything was ablaze in thirty seconds", said the lorry driver, who ran away quickly as "behind me all hell broke loose. In a few minutes the tunnel was like an oven".

There is speculation that the fire on the train between Cairo and Luxor was caused by an explosion of a gas canister used by passengers heating food on the train (not an unusual occurrence in Egypt). Ten of the 11 cars of the crowded train went up in flames. Gas canisters exploded on a train in Guizhou, southwest China, bringing down a railway tunnel and killing more than 80 people.

Fires in steeply-inclined tunnels may be particularly severe because the flame spread has a (rapid) vertical component as well as horizontal. At approximately 7.32 pm on the evening of the King's Cross fire, smoke was seen coming from one of the wooden escalators that was transporting passengers up from the platform levels to the ticketing hall. At 7.45pm the fire suddenly erupted up into the ticketing hall and created severe conditions likened to that of a flashover. The trench effect was seen to cause hot gases in the buoyant plume to lay along the escalator surface and create a rapid airflow which caused these gases to curl over and over towards the next steps above. The airflows in the trench increased in proportion to the size of the fire, eventually creating a flamethrower type effect up and into the ticketing hall.

At Kaprun, a raging inferno developed within minutes as the tunnel, which rises at nearly 45 degrees from the Kaprun station up to the Kitzsteinhorn glacier, acted like a chimney drawing in oxygen to fuel the flames. Driving through or stopping in tunnel is mainly going to affect the probability of having a serious fire in the tunnel, rather than the nature of the fire itself. If the strategy is to drive through, there is a risk that the vehicle may be forced to stop anyway, in which case the fire will be larger than if the vehicle had stopped at once – the Channel Tunnel fire being a prime example of this.

When choosing the strategy, a trade-off must be made between the easier fire-fighting and evacuation possible outside the tunnel (or at a Metro station), and the likelihood of having a larger fire to tackle should the situation get out of control. (Invariably, after a fire disaster, the strategy will be criticised whatever option was chosen. Such is the benefit of hindsight.)

Rapid Smoke Spread

Smoke may spread rapidly in the confines of a tunnel, particularly when large quantities are being released by a fast-growing fire. It may also spread over long distances. Many other incident descriptions have noted how rapidly the tunnel becomes smoke-logged.

Three fatal mine incidents in the UK have been described (Roberts, 1988): 80 died in 1950, 47 died in 1959, and 9 died in 1967. All these cases had very rapid fire growth, so people were overtaken while escaping. Most of the people who managed to leave the train at Kaprun tried to escape up the tunnel but were overtaken by smoke. Two minutes after the crash in the Tauern tunnel, the control video cameras at the northern portal suddenly showed thick smoke coming up the tunnel at high speed. It took only seconds to obstruct the cameras' view to the point they only showed a black image. (800m ÷ 120s = 6.7m/s)

An indication of the rate of spread of smoke in the Huguenot tunnel is given from the times of detector activation. In 12 minutes, a detector 768 m down the tunnel from the point at which the fire started was activated. (768m ÷ 720s = 1.1m/s, normal adult walking speed.)
As an illustration of the distances that are affected, the smoke at Kaprun killed a driver and a passenger on another train 800 metres away (higher up the tunnel), also three people were killed at the station 2600 metres away at the top of the tunnel As an even more extreme example, the first aid camp set up outside the Tauern tunnel had to be evacuated, about 4 hours after the incident started, as the smoke lying in the valley made respiration impossible. Tunnel ventilation systems may accelerate the spread in one direction, increasing the risk that people heading in that direction will be engulfed.
At Mont Blanc, the Italian side of the tunnel was sending air in, rather than extracting smoke (which the French side did within three minutes). The Italians claim that the air influx was beneficial, allowing their

rescue squad to save at least ten people. This was after deaths had already occurred on the French side of the tunnel. The French on the other hand claimed the air influx fed the fire, and drove smoke in the same direction as people fleeing back to the French exit. One of the fatalities was found more than 500m from the fire origin.

The fire in the Tauern tunnel occurred near the northern exit. Ventilation fans swept fumes and smoke to the same north exit, so rescue teams could not enter into the Tauern tunnel from that direction. People heading for the north exit would have been engulfed in the smoke. The tunnel in the Baku Metro was equipped with a controllable ventilation system. The ventilation was set on exhaust mode and much of the smoke was drawn in the same direction as the evacuation was going. From fire-fighters' accounts of the Kings Cross fire, the piston effect (as trains passed through the station tunnels some levels below the escalator itself) did play a major part at various stages of the fire's development in creating a more intense fire.

Opening and closing of doors will affect the movement of smoke. In the Channel Tunnel, the Chef de Train opened an exterior door on the club car in an attempt to find the cross-passage. Smoke immediately entered the club car, which was occupied by 33 people. He then closed the door, but it was reported that the smoke was so heavy that people were required to lie on the floor in order to breathe. Eventually people in the staff car and the truck drivers managed to locate and evacuate through the door into the parallel service tunnel. Over-pressure from the service tunnel door created a fresh air bubble which helped the evacuation.

Some reports of the Salang tunnel fire say that when the accident happened the tunnel was sealed at both ends by Russian military. This is because they thought that an ambush had taken place and they wanted to prevent the escape of the terrorists. This sealed in the smoke as well as the people. Due to extreme cold (the Salang tunnel is over 2500m above sea level) many drivers left their engines running, and exhaust fumes may have contributed to the toxic atmosphere. The sealing of the Salang tunnel might be considered a unique incident, but sadly this was not so. In 2001, three people suffocated when snow driven by high winds blocked up both entrances, trapping as many as 250 vehicles in a poisonous chamber of carbon monoxide exhaust fumes.

Impact of the Fire Environment

Visibility in the Channel Tunnel fire was estimated to be about 50cm. One consequence was the inability of the driver of the incident train to identify its precise location by reading the cross-passage door marker number. As a result, 23 minutes were lost before it was known which cross-passage door should be opened and incorrect information was given to the First Line of Response team.
Eye witness accounts emphasise the difficulty of moving in reduced visibility conditions.

- Zarifa (Baku Metro): "It was pitch black and we couldn't see each other any more-only feel… We groped along, somehow managing to hold onto each other and find our way out."
- Un-named lorry driver (St Gotthard): "The smoke got thicker and thicker and it got to the point where I couldn't see any more. I felt my way down from my cab pressing my hands against the wall and reached a door through which I was able to gain access to the service tunnel."
- Marco Frischnecht, Swiss lorry driver (St Gotthard): "Luckily, I drove there every day and I know where all the emergency exits are," he said. "It was dark. You couldn't see a thing, not even the lights along the edge of the tunnel. "I tried to reverse like many others, but there were so many people I had to give up. It was chaotic and very hot. There was smoke everywhere. I left the truck and I had to feel my way along the walls but eventually I found the emergency exit."

Large numbers of those questioned after the fire in the Zurich metro were moving through smoke from the very beginning. One person said "the air was so filled with smoke and it was so dark that I could not see the ground, or my own feet, or people standing next to me." Another person said "as soon as we were out, the smoke was thicker. It sank down from the ceiling. But visibility was still quite good, so we could see the walkway for quite some time."

The lighting was only effective as long as smoke did not fill the entire cross-section of the tunnel. Afterwards, one person said "I saw the knee-high light only when I was standing right in front of it". The evaluation of the interviews showed that rapid movement is insured by an obstacle free walkway. If it is not possible to remove obstacles, then the handrail must guide people around them. However, very few people noticed the handrail mounted on the tunnel wall.

Even if the lights are not totally obscured by thick smoke, they may nevertheless fail, to leave the tunnel in darkness. This factor was mentioned in accounts of Bethnal Green, Kaprun and Taegu where an apparent lack of emergency lighting left victims groping in the dark after the lights went out. The Homer tunnel did not have any lights at all. Further eye-witness accounts highlight the difficulty in breathing.

- Zarifa (Baku): “But then we couldn't scream any more. We were gasping for breath. It was as if some type of gas was permeating through the train. Our eyes started to water. It was pitch black and we couldn't see each other any more-only feel.”
- Dilara (Baku): “As the smoke and gas began to fill the car, I grabbed my two daughters and buried their faces into my chest, holding them close so they wouldn't breathe the fumes… The air was so bad, we were all coughing. It was so hard to breathe. Then I collapsed and felt like I couldn't go on any more.”
- Irada (Baku, aged 19): “When the smoke started filling the train, I felt I couldn't breathe anymore. I thought it would be easier to breathe in the tunnel, but it was the same. ... Smoke was everywhere. I felt myself totally lost and ready to collapse.”
- Rizwan (Chancery Lane): “Most people's faces went black and they couldn't breathe properly”.
- Jo Lewis (Chancery Lane): “The driver himself couldn't even breathe himself. His face was all black.”

In the Tauern tunnel fire, people covered in soot ran for their lives, gasping for air. In the Zurich fire, the smoke irritated eyes and respiratory systems almost immediately. Passengers protected themselves by holding cloths in front of their faces. In spite of a normal walking speed, people were exhausted after advancing only a few hundred metres. The last passengers left the tunnel roughly 20 minutes after the burning train came to a standstill. The longest escape out of the tunnel was about 700m. In spite of a prompt self-rescue and the generally favourable conditions, many people had run out of strength. This clearly shows the limits of self rescue.

1.6.3 Means of Communication

This section is mainly applicable to stage 1 (Recognition) of the overall evacuation process. However it also has relevance to the other stages, with regard to seeking more information (stage 2: Response) and choosing / being directed to an exit (stage 3: Escape). Canter (1985) suggests that behaviour during a fire emergency is characterised by the search for confirmatory information. At the same time the early stages of a fire are characterised by ambiguity. Alarm messages that give information rather than blaring horns or ringing bells 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.

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 modes of egress there is a need to break the instinctual type of reaction.

4. An individual's cognitive processing ability is limited in emergencies, and procedures will be effective only if well trained. 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.

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 (smoke, flames).
2. The building provides information through alarm or messages via the PA system
3. Information provided by others, staff or other, by what they say or what they do.

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 and 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. They also 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.

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.

Communication between different levels of the Authority Hierarchy

The formal and informal organisational complex is important in guiding behaviour. For example, if lines of communication are poor they will continue to be so in an emergency. Lines of communication should be open, short, and direct to people with authority. However, in the particular case of the Baltimore tunnel accident, the fire department was not notified until over an hour after the accident, and the city's warning sirens weren't sounded until 2.5 hours after the accident. The Bethnal Green incident started when a woman left a bag on a train. Due to heightened security fears (one person had been killed by a terrorist bomb at Victoria station the previous day), this train was evacuated and other trains halted in the tunnel. With better links between London Underground and the various emergency services, it was estimated the whole incident could have been over in about half an hour. This was the time needed to realise the bag was harmless, when the woman who left it behind returned to retrieve it but was halted by police. Instead there were delays in passing this information back, and it was eventually decided to evacuate the other halted trains – this is when two trains accidentally coupled, producing smoke which caused the Line Controller to cut the power, and requiring the trains to be evacuated in situ. The whole process took about 5 hours.

Recommendation 19, of 36 produced by the Channel Tunnel Safety Authority after the fire, was that members of staff who because of their function are likely to observe fires or smoke on a train before it enters the tunnel, should be equipped with a means of direct communication with the Rail Control Centre. Such links were not in place at the time of the fire. Recommendation 32 was that the procedures for the passing of information in an emergency between trains and the Rail Control Centre must be reviewed.

The engineer on the Kaprun train reported the break in electricity supply, via train-phone to the engineer in the top-station. A worker there overheard the call and told it "immediately" to the operating-director. There was no direct link from the train to the director, it seems. The director wanted to reverse the train (out of the tunnel). But by this time "the doors obviously have been already opened and most of the passengers outside the cabin. They would have been endangered by the downhill running train." Unfortunately the director had no way to realise that his assumption was false, and that people were still trapped on the train.

"The incident was more serious than it should have been because the emergency procedures were too complex and demanding and the staff on duty had not been adequately trained to carry them out," said Roderick Allison, chairman of the Channel Tunnel Safety Authority. The procedures which the Rail Control Centre operators had to apply during the incident were difficult to use, were too complicated, too numerous and badly presented. The excessive use of logigrams and too many options such as Heavy Goods Vehicle shuttle train or not, crossover doors open or closed, Amenity Coach at the front or rear of the train and the incident train moving or stopped, all made immediate action by the operators difficult. The Rail Control Centre had insufficient time to correctly carry out all the necessary procedures because four minutes were lost between the first unconfirmed alarm and the first confirmed alarm. A number of recommendations (http://www.railways.dft.gov.uk/ctsa/18nov96/chap9.htm#9h) were made to treat "unconfirmed" alarms as if they were genuine (and also in parallel to reduce the incidence of false alarms).

There was suspicion that the Taegu disaster was made much more catastrophic due to numerous failings by members of staff, particularly in the control centre. The driver of the 1079 train (the first involved) was under investigation on the suspicion of failing to make an emergency report to the station's emergency control centre after being made aware of the arson attack. Four employees from the control centre and one other official from the station allegedly failed to pay attention to the station's closed-circuit TV monitors or give appropriate instructions to the train drivers. The police questioned the engine driver of the No. 1080 train as well as two staff from the control room and found that the driver only received a "driving warning" before entering the Jungangno Station and only received news of the fire after stopping at the platform. Worst of all, officers said they also found evidence that recordings of the conversations between the 1080 train driver and the control centre had been manipulated to some extent before being submitted to the police. Among the previously deleted portions was an order to the conductor to "kill the car"—to remove the carriage's master key and flee. There was no discussion of attending to the passengers. The conductor did as he was told, which locked the carriage doors, trapping more than 100 people who might otherwise have escaped.

It is essential that communication systems remain intact with adequate information flows between relevant personnel. Failures of the human component of the system have already been discussed. However hardware components may also fail. Many members of the authority hierarchy have radios which allow them to communicate when not in personal contact. However the loss of radio contact has been a feature in several of the tunnel fires.

The engineers on the train in the Baltimore tunnel tried to radio the CSX dispatcher to give notice that the train had stopped in the tunnel, but they were in a dead zone in the tunnel and were not able to get through on the radio. One of the engineers used his cell phone to reach the train master and told him that the train had come to a stop in the tunnel. Twenty-seven minutes after the ignition of the fire in the Tauern tunnel, the heat was so intense the firemen had to retreat to the next emergency phone – their radio was no longer working. The driver of the Kaprun train reported the fire and brought the train to a halt which also stopped the descending, counterbalancing train. He was able to communicate with the control centre for some 5-10 minutes before radio contact was suddenly lost. He was told to open the doors to the train, but the loss of radio contact meant the control centre was unaware of his failure to do so.

Accounts of the Tauern tunnel and the Huguenot tunnel both mention that the CCTV cameras were quickly rendered useless, due to thick smoke and/or power failure. Other than helping to raise the alarm, they could not be used to provide much information to the control centre, or enable the control centre to direct operations within the tunnel.

<u>Communication From "Authority Figures" to Members of the Public</u>

Communication in crowds is slower and more difficult. This is even worse if technology for mass address is not present, operable or adequate; there is also the possibility that noise generated by large numbers of people may mask any public address. The US life safety standard NFPA 130 includes noise as a tenability criterion.

Research evidence from Kings Cross and other disasters can be used to propose certain principles to be followed in design, management and training.

- Information should be given rapidly.
- Information should be informative.
- Early action should be emphasised.

The need to persuade passengers to act appropriately is a key focus of emergency response; they must be provided with the maximum amount of information. Much of the delay frequently seen in evacuation is associated with people seeking confirmation before starting to act "abnormally".

Following the Channel Tunnel fire, the statements taken from the Heavy Goods Vehicle drivers show that all the passengers felt that they received insufficient information, both at departure and during the incident. Regular users of the tunnel have also pointed out this regular deficiency and that it is rare to receive information during an incident, such as a sudden halt.

Revised procedures (Berman & Ody, 1995) for the Channel Tunnel include:
- pre-departure information to explain required responses in emergencies;
- pre-departure information to indicate what information will be given at the time of an emergency;
- all information sources routinely used during the journey, to maintain passenger familiarity with them;
- adequate "attention-getters" to highlight the change from routine to emergency information;
- during emergency, clearly and unambiguously indicate what actions are required, and when action should be taken;
- confirm required actions by provision of diverse messages;
- used spontaneous, directed, messages to support the pre-planned information, wherever possible.

Other tunnels also provide the public with pre-departure information. The San Francisco BART has safety brochures in English, Spanish and Chinese available at stations (Chan & McCleery, 1995). Following the St Gotthard fire, Swiss customs officials now hand out safety brochures to truck drivers, and the federal government works with Swiss cantons to make tunnel safety part of truck drivers' training. Mont Blanc tunnel also provides a pamphlet to drivers. One may speculate whether any user would take the trouble to read these, or if they did, would have remembered what to do if an emergency occurred.

There were two major complaints regarding lack of information, following the Cross Harbour tunnel fire in Hong Kong. Firstly, the radio broadcasts by the tunnel company about the fire were confusing. Some earlier broadcasts advised tunnel users about the breakdown of a vehicle, while later broadcasts advised about a car on fire, causing confusion to the people inside the tunnel. Secondly, some motorists and bus passengers complained that they were trapped in their vehicles for some time before being directed to evacuate. Also, no clear messages were given to them while they were waiting to be evacuated.

Where authority figures are in direct contact with the public, verbal communications and gestures may be used. At Zurich, the conductor ran through the train declaring that there was a fire in the tunnel. At Chancery Lane, the driver did this.
- Marian Cassidy (eyewitness, Chancery Lane): “There was smoke and everything and the driver came on and said everyone to get to the front of the train and started shouting 'mayday'”.

Where direct contact is not possible, loudspeakers / PA systems can be used. Messages could be pre-recorded, or improvised on the spot. In the Channel Tunnel, the crew of the train used to evacuate the injured had some difficulties in reassuring the train passengers, as no pre-recorded messages adapted to this situation were available. An improvised message may contain mistakes, or may not inspire confidence due to the way it is delivered. "A nervous voice spoke over the loudspeaker: please wait, do not leave the train! (Fermaud, Jenne & Muller, 1995) Although the tone of voice from the loudspeakers seemed uncertain, the passengers on the Zurich train heeded this advice in this case.
Even if messages are given, they may not always be received or understood. In public assembly buildings, the following percentages of the total population were disabled (Boyce, Shields & Silcock, 1999a; Shields & Boyce, 1995): sight - 1.4% (0.01% blind), hearing - 2.2% (0.24% deaf), mental 2.2%, etc.

In the Zurich tunnel, passengers often recognised fire-fighters only at the very last minute, and could not understand them due to protective masks (Fermaud, Jenne & Muller, 1995). A number of tunnels provide information to drivers by means of radio broadcasts (Legislative Council Panel, 2000; Private Communication, 2002). Questionnaires issued to drivers using the Gudvanga tunnel in Norway found that 36% always listened to the car radio, 49% listened sometimes, and 15% had no radio (Amundsen, 1992).

Multi-lingual issues are important for major European tunnels. At St Gotthard, safety systems included alerts sounding in four languages within minutes of the outbreak of the fire. (Spare a thought for South Africa, which has no less than 11 official languages!)

Communication From Members of the Public to “Authority Figures”

Members of the public will interact with authority figures to raise the alarm, seek information, or ask for assistance. When it comes to raising the alarm, it is clearly beneficial for systems to be in place to facilitate this. At Kings Cross, a ticket collector was told by members of the public leaving the station that there was the fire on one of the escalators. This was clearly very ineffective since the passengers had walked some distance from the fire, the message had to be given by several members of the public before action was taken, and the person being warned was not one “in authority”. On the other hand, when one of the passengers pressed the emergency stop button on the burning escalators, the transport police immediately went to investigate (Tunnel Management Internaional, 2000).

Various newspapers raised questions about an apparent lack of communication equipment and alarms on the Taegu subway train. Suggestions included an emergency telephone with direct line to the driver should be accessible in every car, and a fire alarm button which would if pressed immediately inform the driver about a fire and where the fire was located. As an extension to the local fire alarm in the train, the fire alarm could be linked to the subway system control centre to aid a quick response to a fire. For this particular incident it is not clear that these extra systems would have been of any use. In the Taegu subway, the problem was not that “authorities” were unaware of the fire, but rather that they failed to take prompt and effective action. Communication failures were more an issue within the authority hierarchy, rather than between passengers and authorities.

In other circumstances it clearly is beneficial to have a means of communication from public to authorities. (Most lifts in public buildings, for example, have telephones to the building controllers, not so much to inform them that the lift is stuck, but to provide reassurance when required that action is being taken to remedy the situation.) In the Zurich metro, smoke was entering the carriages of the second train because the air conditioners could not be turned off. "The vents pulled smoke so quickly that soon you could not see through the wagon. Some people were shouting: turn off the air!" (Fermaud, Jenne & Muller, 1995). Shouting was the only way the people in the carriage had of attempting to communicate with the driver. Mobile telephones may be useful in communicating with the emergency services The guardian newspaper, third of April 1999; www.cnn.com/2001/WORLD/europe/12/21/tunnel.reopen/?related), but will not be able to talk to people in authority directly involved with the incident.

Communication Between Members of the Public

Unlike the other forms of communication in the previous sections, systems are not in place for members of the public to communicate with one-another. They are restricted to direct verbal messages, or gestures and other visual communication. Some form of communication occurred in all of the tunnel fires reviewed.

At Kings Cross, members of the public attempted to direct other people away from the burning escalator, although these attempts were frequently ignored (Canter, Donald & Chalk, 1995). In the St Gotthard tunnel, Bruno Saba, a Spanish lorry driver, was more successful in giving directions. He said "I got out of my truck and got the incoming traffic to back up since we were quite close to the exit. I don't know anything else." At Mont Blanc the driver of the burning lorry survived, warned by the flashing headlights of oncoming vehicles. At Zurich and Chancery Lane, the movement of some passengers to the front of the trains encouraged others to follow suit.

Cell phone calls to relatives

Ownership of mobile phones is now widespread in many countries, and this has led to a new option for behaviour patterns in fire. In addition for making it easier to call the emergency services for help, people may also make calls to their relatives (who are not in the fire). This behaviour was noted particularly during the Taegu disaster. Although only a few of the relatives were quoted in these articles, what is interesting is that they were all people who would probably have been the group leader had they and the caller both been present in the fire. One man was called by his wife, and three women were called by their daughters. The relatives being called tried to fulfil their "leadership" role by giving encouragement and advice.

Kim Bok-sun, 45, said her missing daughter, 21-year-old Kang Yeon-ju, telephoned her in a panic. "She only said that there was a fire and the train door wasn't opening, so I told her to just break open a window and get out," Kim said. She called her daughter back a few minutes later but received no answer.

Jang Gae-sun, the mother of another victim: "She said: 'Mum, there is a fire in the subway and I can't breathe'. I urged her (Lee Seon-young, a 20-year-old college student) to pull herself together, but she hung up the phone saying she couldn't talk any more. It was too hard to breathe. The last thing she said to me was, 'I love you, mother'."

1.6.4 The Response Phase

Non-Egress Activities

"Authority figures" have a wide range of non-egress (or pre-egress) activities that are connected with their roles and training. What is interesting is the extent to which members of the public also engage in very similar non-egress activities. It is not clear to what extent these activities are intrinsic to being "a member of the public", or whether members of the public decide to act as surrogate "authority figures". If the latter, we would expect to see individuals exhibiting sequences of "altruistic" behaviour; if the former, altruistic behaviour would occur randomly, with no correlation between individuals exhibiting one aspect of altruistic behaviour and another aspect. Not all pre-egress activities are altruistic, or even constructive for the individual. At Tauern, there was evidence of "carelessness and an uncaring attitude" - one lorry driver said "they left their cars, had a look around, and a German driver was taking pictures" (The Observer newspaper, 28th of March 1999).

Investigate
A ticket collector at Kings Cross Underground Station was told that there was a fire on one of the escalators. His response was said to be "you're the third person to say that, perhaps I should go and look". In contrast, when one of the passengers pressed the emergency stop button on the burning escalators, the transport police immediately went to investigate. The police are expected to respond rapidly to any cue; ambiguity of the cue is not important, since investigation is appropriate in many cases. In contrast the role of the ticket collector is to collect tickets and perhaps assist passengers. Investigation is not a central part of his duty. This clearly demonstrates that the roles and responsibilities people have prior to the emergency are likely to have a considerable influence on what happens during it.

First-aid fire fighting, and other attempts at mitigation
This section is concerned with the fire-fighting attempts of people in the tunnel at the time the fire starts, or very shortly after. It does not cover the activities of fire brigade personnel.
On the bus in the Huegenot tunnel, the co-driver attempted to smother the flames with clothing which promptly caught fire. No one thought to use the fire extinguisher onboard the bus, or any of those

available in the tunnel. The tunnel extinguishers were only 50 m away. Had the co-driver or passengers acted quickly the fire might have been brought under control at an early stage.
In the Mont Blanc tunnel, the Belgian lorry driver survived, warned by the flashing headlights of oncoming vehicles, but had "no time to use his fire extinguisher - so he ran for his life through the tunnel".

A questionnaire on driver behaviour in the Gudvanga tunnel in Norway (Amundsen, 1992) elicited the response that 43% would have tried to extinguish the fire. However another study based on statistics of actual practice (Arnaudet, 1999) contradicts this, saying most drivers would attempt to drive through the tunnel before tackling the fire. Automatic logs during the Tauern tunnel fire show that the first extinguisher was taken out of its housing 5 minutes after the crash. However, from subsequent events it was clear that these had not been used effectively, since the fire kept growing. Fire-fighting by train passengers did not feature in the incidents covered by this review. On the Kaprun funicular railway, there were extinguishers in the engineer's room in both the bottom and in the top stations, but not in the train cabins or the tunnel itself, because legislation did not require this.

Following the Taegu fire, the Korea Times lamented an "absolute lack of safety education" for people in emergencies, "The passengers could not do anything except panic with no one attempting to use the fire extinguishers placed under the seat," it said. The Seoul Metropolitan Subway Corporation conducted an emergency drill following the Taegu fire. In the drill, two-thirds of the participants said they were aware of the locations of the fire extinguishers on the trains, but it took as long as 33 seconds to find them. The blaze on the subway car in Taegu was raging in less than 10 seconds.
Of the 38% of the people who said they know how to operate the extinguishers, only three were women. Two of them were nurses and the other a kindergarten teacher. They said they learned to handle the fire extinguishers at work.

The Taegu fire was started deliberately. Passengers, who were near the arsonist when he threw the flaming bottle inside the train, unsuccessfully tried to stop him. Other types of mitigation activity, performed by people "in authority", may be more successful. During the Bethnal Green incident, two of the six (!) trains involved coupled together accidentally, with the result that the motors on the rear train were driving forwards while the forwards train had its brakes applied. The motors overheated, forcing lots of smoke to be generated. The Line Controller took immediate action and turned off traction current for the section the train was on, thus immediately stopping the production of smoke.

In the Howard Street tunnel, Baltimore, noticing that the fumes from the diesel engines were growing worse (the engineers did not know at that point that several cars had derailed and a fire had broken out), the engineers shut down the two rear engines, uncoupled all three engines from the train, and exited the tunnel at the north portal. From the above, it appears that first-aid fire-fighting is rarely carried out. Where it is attempted, the fire is at the early stage so there would be a reasonable chance of success, in line with Woods' findings (Canter, 1990; Wood, 1972) for building fires.

It must be remembered though that the survey of tunnel fire incidents has concentrated on those serious enough to be newsworthy, and in common with building fires there may be a (large) percentage of unreported fires where first-aid fire-fighting has been successful. One of the Mont Blanc references (Fire Prevention, 1999) said fires in vehicles passing through the tunnel were "commonplace". However, when conducting a risk assessment, if the frequency of (serious) fires is based only on those recorded (ie ignoring more frequent fires where fire-fighting was successful), then as far as modelling goes, fire-fighting actions should be excluded in order to prevent the risk estimate being too low.

Provide information / reassurance

Train staff would often provide passengers with information, either by PA or face to face. The manner in which this information was given was not always reassuring. In the Zurich metro (Fermaud, Jenne &

Muller, 1995), passengers on the first train were warned by PA. Although the tone of voice from the loudspeakers seemed uncertain and nervous, the passengers heeded this advice (to wait until told to leave). Those who tried to disembark were held back by fellow passengers. Passengers on the second train remained seated, but knew that something was wrong when the conductor ran through the train declaring that there was a fire in the tunnel. There were different moods on the various exit platforms of the second train. In one wagon, there was impatience; loud shouts and blows were directed at the closed doors. In another wagon, advice was given, moist cloths were distributed and silence prevailed. Towards the end of the evacuation of the Zurich tunnel, the presence of rescuers encouraged the escaping passengers to continue and to reach the portal. Several people were unsure if they could have made it without presence of rescuers. Following the derailment at Chancery Lane, various witnesses described how the train driver reacted. According to these statements, information was provided, but the tone was far from reassuring.

- Jo Lewis: “We could hear the driver going 'mayday, mayday everybody get off'. “
- Marian Cassidy: “There was smoke and everything and the driver came on and said everyone to get to the front of the train and started shouting 'mayday'.”
- Cris J: “The driver said, 'Mayday! Mayday!', then, 'Help! Help!' there was a fire at the back of the train, and told everyone to leave as fast as possible.”

In contrast, the performance of the incident train's crew during the Channel Tunnel fire was good. In particular, the calmness of the Chef de Train and catering steward helped to prevent the passengers from panicking in the Amenity Coach, under very difficult circumstances (the door had been opened, filling the coach with smoke).

Provide directions / instructions / orders

At King's Cross, there were numerous instances where members of the public and London Underground staff attempted to stop people entering the main ticket hall or use the Piccadilly line escalators. Most of these attempts were ignored by other members of the public (Canter, Donald & Chalk, 1995).

The ineffectiveness of the London Underground staff arose from the low respect in which they are held by many members of the public. The principal encounters between the staff and public will be when some delay or other inconvenience, such as an escalator routinely out of order, has occurred. Under these circumstances the underground staff are likely to be powerless and ill informed, and thus in an emergency perceived as irrelevant also.

The police at the station managed to get people to follow instructions with little exception. The influential role of the police stems from people's reaction to them as figures of authority in general. Members of the London Fire Brigade were also successful in directing people (www.firetactics.com/KINGSCROSS.htm).

Members of the public were more effective at directing others in the St Gotthard incident. (This may have been because the fire was already obvious to those being directed, unlike at Kings Cross.) One of the truck drivers survived the crash. Bruno Saba, the Spanish lorry driver, said "I got out of my truck and got the incoming traffic to back up since we were quite close to the exit. I don't know anything else."

Police said emergency procedures worked properly as barriers automatically stopped more traffic entering the St Gotthard tunnel. At the Tauern tunnel on the other hand, many drivers simply passed the red lights and continue into the tunnel. A similar test was made some months later at another tunnel for a TV report and it also showed lots and lots of cars ignoring the traffic lights. Traffic lights present no physical obstacle, and also do not say why entry to the tunnel is not allowed. Without additional information, a prolonged red light may simply be taken for a malfunction, and once the first drivers ignore it, others will follow.

In the Channel Tunnel, once the cross-passage had been located, the Chef de Train then proceeded to evacuate the passengers and crew from the club car and into the cross passage. Minimal direction would have been required, once the order to leave was given. On trains, the “authority figures” may or may not be present in person to provide directions and order people to leave. Emergency procedures for the San Francisco BART (Chan & McCleery, 1995) were drawn up following the fire in 1979. The train operator will issue evacuation instructions to passengers private train the public address system. The passengers at Zurich gradually headed to the front of the first train, partially due to the instructions coming over the loudspeakers and partially because other passengers were doing so. Passengers were clearly instructed by the train personnel not to disembark immediately. On the second train, as on the first, disembarkation took place when a clear summons from the train personnel had been given (Fermaud, Jenne & Muller, 1995). It was also pointed out to passengers that the distance to the portal was 500 m.

More recently, four trains were stuck following a fire in the tunnel at Schiphol airport, Amsterdam. "There was no danger for the passengers, but if they were not evacuated they would have been trapped in the tunnel for another few hours," Schiphol spokesman Ruud Wever said (news.airwise.com/stories/2001/). It is not clear whether personnel directly ordered people to leave the trains, or used PA systems.

Search / warn / rescue

The actions of the train crew / drivers at Zurich and Chancery Lane could be considered to constitute a search and warn pattern (although they have been described above under providing information / reassurance). Members of the public do not seem to have engaged in searching and warning; rapid fire growth in many cases may have made this option too hazardous and in any case, all members of the public would have been alerted at much the same time. Search and rescue operations will usually be confined to fire brigade personnel. Given that they will probably have to travel some distance before they get to the seat of the fire, anybody they rescue will need to have taken shelter in some sort of refuge - either an officially-designated one, or improvised. Examples of the latter include the Channel Tunnel train driver, who was found in his cab by the First Line of Response team and led to safety; the three people at Tauern who were rescued from an emergency telephone box; and 12 drivers rescued from their vehicles by Italian operatives at Mont Blanc. A tunnel maintenance worker, riding his motorcycle, saved 10 people in four journeys into the tunnel. On the last journey, he died in a refuge with a person he tried to save.

One member of the Huguenot tunnel operating staff had driven into the tunnel. His vehicle was immersed in dense smoke and therefore he drove his way out again, feeling his way along the reflective studs in the centre line of the tunnel, all the time calling out to anybody still in the tunnel. Fortunately there were no people overcome by fumes lying in the road were they could be run over by his vehicle while he was doing this. (At Tauern, firefighters walked in front of their vehicle to prevent accidents like this)

Other rescue actions may be more spontaneous, where the rescuer is not specifically searching the building looking for people in need of assistance, but encounters them in the course of doing something else. At Kings Cross, Station Officer Colin Townsley was directing operations from the ticketing hall. He was not wearing BA kit, and died trying to rescue a woman who had entered the ticketing hall as the fire suddenly erupted (www.firetactics.com/KINGSCROSS.htm).

Rescue actions may cause problems for other people. During the Bethnal Green incident London Underground staff, and those from the emergency services, were moving in the opposite direction and impeding the flow of passengers. This was really only a problem due to the narrow tunnel and the large number of people attempting to evacuate. Members of the public may also rescue people they encounter.

- Irada (eyewitness, Baku, aged 19): "I felt myself totally lost and ready to collapse. That's when I made myself call out for help. A guy reached out and somehow found my hand and pulled me to safety."

Rescues may only involve short-lived assistance, abandoned as soon as an obstacle has been surmounted. Zarifa (eyewitness, Baku), said "Young men tried to break the glass of the train windows with their bare fists. Finally, some succeeded and managed to lift us through …". During the Zurich evacuation, passengers remarked in particular that people helped one another and that no one shoved. The older people were assisted by others. Among the instructions given during an emergency on the San Fransisco BART, passengers are requested to co-operate and assist those who may need it. Procedures for the evacuation of the Heathrow Express Trains (French & Stevens, 1999) include a requirement for members of staff to control the disembarkation, and request the help of suitable members of the public to assist other people who would otherwise have difficulty getting off the train.

Unlock doors

On most rail systems the opening of the doors is controlled by the train staff. In the Channel Tunnel the Chef de Train (CdT), who is in overall charge of the train, opened an exterior door on the club car to determine what was wrong, and smoke immediately entered the club car, which was occupied by 33 people. He then closed the door, but it was reported that the smoke was so heavy that people were required to lie on the floor in order to breathe.

In some of the worst disasters (Baku, Kaprun, Taegu), the train doors were not opened, either because a power failure made this impossible, or the staff neglected their duty. The latter reason was suspected in Taegu, where the driver of the second train allegedly fled the scene without opening the doors, taking the master key with him, and leaving passengers trapped in their compartments. It took almost 2 minutes for a student taking part in the drill on the Seoul subway system to get out of the train by manually opening the doors. Victims of the Taegu fire would have had about 57 seconds to get the doors open before being smothered by the flames and smoke. About half of the 50 subway passengers interviewed in Seoul yesterday said they know how to operate the emergency equipment inside the trains that are used to open the doors manually.

Follow training / use of BA kit

Members of staff will usually behave in accordance with their training, but mistakes can be made. The training and procedures may also turn out to have been flawed after the incident.

For example, in the Channel Tunnel fire, the initial decision to drive on through the tunnel, and the subsequent decision to stop there, were both in accordance with the procedures at the time. Both of these actions were revised, among the 36 recommendations following the inquiry after the fire. One area in which training seems to fail quite frequently is in the use of breathing apparatus. The driver in the Channel Tunnel tried to leave his train to prepare the evacuation and open the cross-passage door (in accordance with the procedures). The presence of dense, opaque smoke prevented him from carrying out this operation. He did not use his breathing apparatus because he considered it impractical.

The two recovery staff who first arrived at the incident site in the Hong Kong Cross-Harbour tunnel had not fully complied with the standard emergency procedures.

- they did not wear smoke masks when entering the scene.
- they used a fire extinguisher instead of a fire hose to control the fire.
- one member of the staff left the scene to help with the evacuation, but should have stayed to work as a team.
- both members of the staff should have stayed at the scene to hand over the operation to the fire officers on their arrival.

According to the report from the rescue staff, as they did not wear smoke masks, they felt uncomfortable because of the heavy smoke and could not stay at the scene. Both staff proceeded to conduct evacuation. Failure to follow standard procedures may put the staff at risk.

The fire brigade is not immune from mistakes either. The fire brigade in the Huguenot tunnel fire scrambled immediately, but did not follow all the laid down procedures and therefore some of their operations were delayed. At Kings Cross, most fire-fighters returned to street level to collect hose and breathing apparatus; however three officers remained in the ticketing hall to supervise the evacuation of passengers. One of these three (the senior officer), Station Officer Colin Townsley, subsequently died after trying to rescue a woman passenger. At Mont Blanc, Chief Tosello of the Chamonix fire department died because there were insufficient BA kits, so he was sharing with one of his men. He had a heart attack following smoke inhalation while sheltering in a refuge with 4 other firemen.

1.6.5 Group Formation and Behaviour

As is well known from fires in buildings, social groups tend to remain together. The tightest bonding is exhibited by members of the same family. One of the eyewitnesses to the Tauern fire said "we ran for our lives, fathers carried children in their arms, gasping for air, running for the exit". Other witnesses heard cries "help, save us, we are burning". People covered in soot ran for their lives. Some of the injured people were in shock, crying and screaming, others were looking for relatives.

Dilara (Baku Metro): “I grabbed my two daughters and buried their faces into my chest, holding them close so they wouldn't breath the fumes… My daughters helped me off the train-I don't quite know how. They fell down from the train, when they tried to run they kept falling, tripping over bodies. The air was so bad, we were all coughing. It was so hard to breath. Then I collapsed and felt like I couldn't go on any more. I begged my daughters to go on without me, to make it to safety-to save themselves. As I lay there, people stumbled and fell over me. It was hell. People at the Depot finally rescued me.”

This last statement is interesting because is shows the family group breaking up under extreme stress. Larger groups may be formed by people who have some form of social affiliation.
The Mersey tunnel fire started in the engine compartment of a coach, on private hire carrying 40 female passengers who were members of a private party on a social night out celebrating a special occasion (Gillard & Arch, 1995). The passengers had consumed a significant quantity of alcohol, which appeared to impair their judgment, particularly their appreciation of danger, impair their ability to behave rationally and quickly in response to the danger, and gave rise to heightened and boisterous behaviour. They required a significant level of resources to take care and control of them.
During an exercise, volunteers have been seen chatting with each other, no one else attempting to overtake anyone else during the evacuation, relative calm and even several volunteers waiting for their friends to catch up. Interviews with these volunteers after the exercise made it clear that they had no preconceptions as to how they would have behaved in a real situation (Marsden, 1999). The author of this reference concluded that deficiencies in drills meant that evacuation models would be more realistic. However, the real deficiency lay in using people who had some affiliation (even if only by virtue of being in the same group of volunteers) to simulate a population without those links.
Ad-hoc groups may be formed by those who have no affiliation beyond finding themselves in the same emergency. A number of incidents have led to groups of people holding on to one-another (due to poor/zero visibility) and moving slowly in single file to the same exit. These groups can provide mutual encouragement for their members: "In one of the lighted niches, the man in front of us sat down. I sat down too and told my girlfriend that I wanted to stay there. She became upset, started shaking the man and screamed that he had to go on". Other ad-hoc groups may be formed from rescuers and the dependents they are helping. The rescuers may include members of the public, unrelated to the people they save.

1.6.6 Reluctance of People to Abandon Property

Cars

Accounts of the road tunnel fires make it clear just how attached motorists are to their vehicles. It is probable that the main reason for this is that they do not want to abandon their journey. There is also the inconvenience of being without transport, should they leave on foot while the car or lorry is left to be destroyed in the car. Although the vehicle will (probably) be insured, all the extra effort involved in making a claim and receiving a satisfactory settlement will encourage the (private) motorist to save his vehicle if at all possible. Finally, people may be concerned about theft, should they leave their vehicle unattended. Motorists are therefore inclined to stay in their cars, and if asked to leave them unlocked, are unwilling to do so (Rhodes & Wong, 2001).

In the unpublished car simulation tests carried out for Eurotunnel, people were presented with cosmetic smoke from a car at the front of the wagon, while seated in their cars. People in the cars behind the "fire" were observed to sit and watch developments, in some cases they just closed their windows to keep the smoke out of their own car. They only evacuated the car and the wagon when they heard an instruction to do so, or saw others leaving.

The procedures for the Huguenot tunnel, under fire emergency conditions, were that vehicles should be left the roadside and driver and passengers take shelter in cross connections (Gray & Varkevisser, 1995). Without exception, when the fire occurred the drivers of cars executed "U" and three-point turns and left the tunnel.

Witnesses from the Tauern tunnel reported how some drivers refused to leave their cars, despite the chaos around them. Others even tried to manoeuvre their vehicles in the middle of the smoky inferno and drive in the opposite direction.

In the St Gotthard tunnel, it was estimated there were about 200 vehicles inside at the time of the fire. About 100 cars turned around and left the single-bore, two-lane tunnel. Once the cars were cleared, a bus full of passengers managed to reverse out of the tunnel, as did about 15 trucks. Some drivers stayed in their vehicles and tried to telephone for help. Of the11 (eventual) fatalities, six of the bodies were found on the tarmac as people tried to reach safety, while the remaining four were in their cars.

There were fewer vehicles in the Mont Blanc tunnel, but these were not able to get out. Most of the drivers, both in trucks and in passenger vehicles, stayed inside or near their vehicle. Of the 10 passenger vehicles, 4 had started to make U-turns, but were stopped practically at their point of departure. 27 of the victims were found in their own vehicle, 2 in other vehicles, and 9 elsewhere in the tunnel / refuges.

The next incident demonstrates the commitment of people to the continuation of their journey. A few hours before the formal opening of the Laerdal tunnel, a fan caught fire in a bus carrying about 50 people from Voss though the tunnel to the ceremony. The bus filled with smoke, forcing passengers to evacuate while 12 km inside the mountain. No one was hurt. The smoke eventually cleared, and all passengers were able to reboard the bus and continue their tour.

Some motorists and bus passengers in the Hong Kong Cross Harbour tunnel fire complained that they were “trapped in their vehicles” for some time before being directed to evacuate. The main ground for complaint was doubtless the delay in receiving information, rather than being with their cars.

<u>Luggage</u>

Only a few anecdotes refer directly to passengers with luggage and other belongings. On August 1, 1970, a fire in the tunnel of the New York City subway near Bowling Green killed 1 and injured 50. The one death occurred when a woman, who returned to the train to retrieve her purse, died of smoke inhalation (www.nycsubway.org/faq/accidents.html). It was suggested that some of those people killed in the St Gotthard had reached safety but returned to their vehicles to retrieve items left behind (www.cnn.com/2001/WORLD/europe/12/21). Whether other people remembered to take belongings with them, or instead left them behind, is not known.

The Huguenot tunnel fire started on a moving bus, which then crashed into the tunnel wall. Despite this, the CCTV recording showed passengers leaving the bus in an orderly manner and attempting to retrieve their belongings from the roof rack (Gray & Varkevisser, 1995). In contrast, the Ritchies bus company treated its passengers to a Queenstown shopping spree after they lost all their luggage in a bus fire in the Homer Tunnel near Milford Sound (onenews.nzoom.com/onenews_detail/ 0,1227,143887-1-7,00.html). A railway official reported personal knowledge of a detrainment, where the passenger population included passengers attempting to evacuate with their luggage (Galea & Gwynne, 2001). Procedures for the evacuation of Heathrow Express Trains recognise that people do not want to abandon their luggage; if people wish to take their luggage, they are instructed to wait behind until all other passengers have left first (French & Stevens, 1999).

1.6.7 The Movement Phase

<u>Running</u>

Although building evacuations assume the population moves at walking speeds, in tunnel evacuations there are many accounts of people running (The Guardian newspaper May 31st 1999; The Observer newspaper, 28th of March and 30st of May, 1999; Fire and flammability Bulletin, May 1999) (or attempting to run). In the Summit Tunnel (Manchester, 1984), a petrol freight train derailed at 40 mph. The driver, guard and an inspector climbed down from the locomotive and went to investigate. They heard a muffled explosion and suddenly saw flames about three wagons away from them. They turned and ran, getting out safely, a distance of 1500m.(However, another report, stated that the 3 people managed to decouple the loco and drive out - given they had 1500m to go, this is plausible)
Attempts to run may be thwarted by uneven ground (for example, railway tracks) or obstacles - including bodies of victims.

<u>Exit (Direction) Choice</u>

The tunnel portal corresponds to the "familiar route" and as such will be the most popular exit choice provided it is not too distant. The bus passengers in the Homer Tunnel were fortunate that the fire occurred just 200m into the unlit tunnel. The Tauern crash occurred about 800m from the northern portal, 5,500m from the south. People who left by the north portal had travelled between 400-800m. In the Zurich metro, passengers on one of the two trains involved had about 700m to travel to the portal; on the other train the distance was only 500m. Only the passenger who pulled the emergency brake escaped in the direction of Zurich main station. All the other passengers moved away from the fire. In the King's Cross fire, there were still passengers exiting from the platforms below in an orderly manner just a few minutes before the fire suddenly erupted. A large number of screaming passengers then exited into the street.

Although King's Cross station consists of a complex system of passageways, there are simple, direct and preferred routes between any two destinations. Regular travellers know these routes well and use them consistently. Overall, the people who died in the fire followed the same structure of behaviour as the survivors. These were in attempting to leave by the routes from which they had originally entered the station, or by their previously intended route (Canter, Donald & Chalk, 1985).

The reluctance of people to leave their cars has already been discussed under the heading of property protection. However there may be an element of exit choice involved as well, as driving to the tunnel portal may be the only way to get there before being overtaken by smoke. The inside of the car may also act as a "refuge", keeping out the worst of the smoke for a short period.

The various emergency exits, cross-passages to parallel service tunnels and refuges will all look the same until the person actually goes through the door and sees what is on the other side. Thus, whether a door ultimately leads to the outside, or to a dead-end refuge, will not be a factor in exit choice.
The single-bore, two-lane St Gotthard tunnel has a parallel escape route accessed at 250m intervals by ventilated galleries. Benno Beuhlmann, in charge of Uri canton's chemical accident unit, described how workers found four corpses in cars and six people who had suffocated in the emergency tunnel, tantalisingly close to exits which would have saved their lives. "But without the emergency tunnel, there would have been many more victims," he added. People on the northern side fled their cars and escaped on foot through the parallel emergency escape route. Two lorry drivers described how they had to feel their way along the tunnel walls, due to zero visibility conditions, until they found an emergency exit. One of them felt he escaped only because he knew the tunnel well. "Luckily, I drove there every day and I know where all the emergency exits are," said Marco Frischknecht, a Swiss lorry driver.

In the Mont Blanc tunnel, the side doors led to dead-end refuges instead. Nine of the bodies of the victims were found outside vehicles. Two drivers of trucks up front, and thus close to the fire, left their vehicles and fled toward France. They probably died of asphyxiation, after having gone about 200 to 240 meters. Among the drivers or occupants of the cars stuck in line, four also left their vehicles. They died of asphyxiation after going about 100 to 500 m. From the distances travelled, these people would have been able to reach a refuge area, yet did not do so.

Five fire-fighters used a refuge -- one of them died of a heart attack, triggered by smoke inhalation, after they were forced to share breathing apparatus (www.mrtunnel.com/page3.htm; New Civil Engineer, 1999). A tunnel maintenance worker, riding his motorcycle, saved 10 people in four journeys into the tunnel. (How did he manage to carry at least 3 people on at least 2 occasions?) On the last journey, he died in a refuge with a person he tried to save. The refuge was close to the fire, which had a duration of 50 hours (New Civil Engineer, 1999;Fire and flammability Bulletin, 1999).

In the Tauern tunnel, 4 lorry drivers tried to take cover inside an emergency phone box about 100 meters from their vehicles but only 2 men and a woman managed to do so; the fourth, a 27-year old man, just failed to make it. The other 3 survived for an hour until they were rescued by firemen.
The bus passengers in the Huguenot tunnel failed to realise that the cross connections were places of refuge, and that they should gather there rather than walk out of the tunnel. The cross-passages were not signed as emergency exits though.

Directions given by people in “authority” are clearly a strong influence, as evidenced by Kings Cross (directions given by British Transport Police; London Underground staff and members of the public were not viewed as “authority” and thus were often ignored), St Gotthard (instructions to back up given by truck drivers, and later police), Zurich (directions to the portal given by the train drivers), San Francisco BART (directions from the train driver; cross-passages to the adjacent tunnel were spaced every 100m), etc.

In the Huguenot tunnel, the cross passages were not used as refuges because they were not signed as such (Gray & Varkevisser, 1995). In the Zurich tunnel, pictograms directing people to the exit were seldom noticed and in one case they invited misinterpretation (Fermaud, Jenne & Muller, 1995). "I saw the pictograms with the running man and thought there must be an emergency exit somewhere else close by". Other people said information about the distance to the portal was valuable.

A paper describes a system of illuminated signs which show the distances to the nearest exit. Each side has two independent illuminated panels, so the tunnel users can either make up their own minds based on the distances shown on the side; alternatively they can be directed at the tunnel controller to go in one or other direction, by only illuminating one side of the sign (Moller-Hansen, 2002). Such signs are only valuable while they can be seen. In a number of the incidents surveyed, there were conditions of almost zero visibility.

Only twelve people travelling on the train at Kaprun escaped with their lives, as they managed to escape through a broken window in the back of the train and evacuated down at the tunnel. Of the 155 people who died, 60 had managed to leave the train, but were quickly overcome by acrid smoke as they tried to flee by running upward on narrow stairs leading out of the tunnel (Petrovitsch, 2000; Andersen & Paaske, 2002). The fire started at the back of the train, so they would have needed to run past the fire in order to go down the tunnel – something which may not have been possible by the time they managed to get off the train.

In Baku, the fire also started towards the rear of the train, and the direction of evacuation was to the front of the train. The ventilation system was sending smoke in the same direction. However due to conditions of almost zero visibility, people would not have been aware of the direction of smoke movement, so this would not have been a factor in their exit choice.

At Mont Blanc, ventilation fans were sending smoke towards the French exit, so the people on that side of the fire died, whilst those on the Italian side survived. Nobody on the French side ran past the fire to the Italian exit.

In the Tauern tunnel, smoke was blowing towards the north portal, driven by strong winds. However as the north portal was a much nearer exit than the south one, this may have been a more important factor in the exit choice. It is not clear whether anyone moved past the fire in this incident. In the Zurich fire, only the passenger who pulled the emergency brake escaped in the direction of Zurich main station (Fermaud, Jenne & Muller, 1995). All the other 140 passengers moved away from the fire.

In building evacuations, people may take account of the size of the queue at each exit, when choosing which one to head for. This was not a factor in any of the tunnel fires examined here; the speed of fire development meant that people had to make their exit choices long before any queues could form. Also, near-zero visibility meant that exits could frequently not be seen when the exit direction choice was made. In fact, people often moved together in single file to a common exit.

Rail Tunnels: Difficulty Getting Off The Train

In order for passengers to leave the train normally by the side doors (the fastest mode of evacuation), the train must be in a station. A large gap between the train and the platform could be a hazard, even if not obscured by smoke, making it possible that people might fall through the gap while getting on or off the train. On the Seoul subway system in March 2002, a 66-year-old man did just that. He died.

If only part of the train is in the station, some passengers may have to move between carriages via the end doors, which are usually quite narrow and therefore introduce a significant delay. In more severe gets still favourable circumstances, it may be necessary to evacuate passengers to the track level. Passengers may use side doors (if the tunnel is wide enough) or the end door. Ladders may be available to assist the descent (typical drop is about 1m). In one incident, 400 passengers required about 1 hour 20 minutes for the passengers to descend to track level. This equates to an average of 12 seconds per passenger to negotiate the exit and ladder. The passenger population in this incident included elderly and infirm people and passengers attempting to evacuate with their luggage.

In another incident (Rose & Harding, 1993), every passenger had to pass through the train end door, 495 mm wide, then descend a wooden ladder with four steps (a vertical drop of 1.2m).The actual full-scale detrainment started at 0858, and was completed at 1330. In the event both directions were used, and even if numbers were evenly distributed, this represents one person for six seconds in each direction. (It is not clear whether the passengers took their luggage with them on this occasion.)

In the Zurich fire, it was possible to leave by the side doors of the train because the tunnel was wider (Fermaud, Jenne & Muller, 1995). (A large cross-sectional tunnel area is a substantial safety benefit that should not be neglected in the choice of tunnel concept. For long tunnels, twin tubes with intervening cross connections should be thoroughly evaluated against a single tube with a large cross-sectional area. It is as important to ensure that the train can be evacuated as it is to ensure safe escape from the tunnel (Andersen & Paaske, 2002). There was a 1 m difference in heights to be surmounted during disembarkation. In addition, the walkway below was cast in shadow. Despite this there were very few falls, with most people experiencing no problem including the train. Passengers remarked in particular that people helped one another and that no one shoved. The older people were assisted by others. In some situations it may not be possible to use the carriage doors during an evacuation, and passengers will try to break windows instead. At Chancery Lane and Taegu, the trains were in a station so the drop through the window was only to the level of the platform.

At Taegu, on the second train involved, police said that of the six cars the doors were locked on four of them – trapping more than 100 people who might otherwise have escaped. Passengers were apparently unfamiliar with levers used to unlock doors manually. (About half of the 50 subway passengers interviewed in Seoul said they did know how to work them, but may have only learnt how from the media after the Taegu fire.) Alternatively passengers may have been unable to use them in the crowded conditions. The lever for the emergency door opener was located under a seat close to the door, and required someone to bend down to operate it. At Kaprun and Baku, the drop from the window was to track level. At Kaprun, all the passengers were skiers and snowboarders, so would have been young, fit and agile, able to negotiate the drop. A ski pole was used to break a window at the rear of the train, which the only survivors used (Petrovitsch, 2000; Andersen & Paaske, 2002). Others also managed to break out eventually. 155 people died, of whom 60 people had managed to leave the train.

At Baku, young men (Navy sailors, by one account) helped other people through the windows, after breaking them with their bare fists. The crowded train and narrow tunnel cross-section contributed to a very slow evacuation, and the people panicked (sic) (Andersen & Paaske, 2002).

The most difficult evacuation of all would involve an overturned, smoke-logged rail carriage (for example, as a result of the Paddington rail crash in England, DATE). Two full-scale evacuation experiments were performed (Galea & Gwynne, 2001), in one of which the participants were subjected to non-toxic smoke. Only a single run of each trial was undertaken with a limited – and uninjured – population. In the evacuation involving smoke, the carriage and exit was found to achieve an average flow rate capacity of approximately five people a minute. Without smoke the flow rate was found they approximately 9.2 people a minute. Due to the nature of experimental conditions, these flow rates are considered optimistic. Fortunately, such a situation has not yet occurred in a tunnel.

There have been a couple of instances where passengers left a moving vehicle. The Cairo train fire (www.emergency.com/firepage.htm) did not occur in a tunnel, so may not be relevant in this situation. In the Huguenot tunnel, some of the passengers panicked (sic again) and leapt from the moving bus, many sustaining injuries in the process (Gray & Varkevisser, 1995).

Disabled and Injured People

Although there are many different forms of disability, the major effects on egress performance are likely to cover movement speed, ability to negotiate obstacles, and stamina. Parameters of the probability distributions for movement speeds of different locomotion aids have been determined (Boyce, Shields & Silcock, 1999a, 1999b), however in a tunnel the terrain may be unsuitable for some types of aid. This will be more of a problem in rail tunnels. For example, passengers in wheelchairs may have to abandon them and be carried instead (Chan & McCleery, 1995). Following the Bethnal Green incident, London Underground now provides "carrying sheets" for evacuating any disabled customer in the event of detrainment (Rose & Harding, 1993).

Vertical drops can provide a serious obstacle. In the Bethnal Green evacuation, every passenger had to pass through the train end door, 495 mm wide, and then descend a wooden ladder with four steps, a vertical drop of 1.2 m. This process took on average 6 seconds per passenger; obviously some people will take much longer than others.

In the Zurich fire, there was a 1 m difference in heights to be surmounted during disembarkation (Fermaud, Jenne & Muller, 1995). In addition, the walkway below was cast in shadow. Despite this there were very few falls, with most people experiencing no problem in leaving the train. Passengers remarked in particular that people helped one another and that no one shoved. The older people were assisted by others. Height differences are not only restricted to rail tunnels. In the Hatfield and Heathrow tunnels, walkways are on raised ledges, which only able-bodied people could use (Marchant, 1999). Bodies of victims can be an obstacle to others, as illustrated by eyewitness accounts of the Baku Metro fire.

- Dilara: "My daughters helped me off the train-I don't quite know how. They fell down from the train, when they tried to run they kept falling, tripping over bodies. The air was so bad, we were all coughing. It was so hard to breath. Then I collapsed and felt like I couldn't go on any more. … As I lay there, people stumbled and fell over me."

Gulnara: "Somehow we found a way to escape through one end of the train. There seemed to be a ladder there. Then all of a sudden I realized this was no ordinary ladder but a pile of human bodies that had collapsed and cascaded down into the train tunnel."

Stamina is another important issue. At Bethnal Green, there were no serious casualties. 33 people went to hospital, suffering mainly from exhaustion (Rose & Harding, 1993). The total number evacuating was about 5,500 people. In the Zurich fire, the longest escape out of the tunnel was about 700 m. In spite of a prompt self-rescue and the generally favourable conditions, many people have run out of strength (Gillard & Arch, 1995). This clearly shows the limits of self rescue.

Some people who would not normally be considered "disabled" may effectively be so. In the Mersey Kingsway tunnel, the passengers of the bus had consumed a significant quantity of alcohol (Gillard & Arch, 1995), which appeared to impair their behaviour. Pregnant women may also require special treatment. The commonest forms of injury will be smoke inhalation and shock, although the extent to which these injuries will impair performance is not clear. A drill was performed in an attempt to convince safety officials that it was safe to re-open the Channel Tunnel after the fire, but this was criticised by some (www.emergency.com/chunnel1.htm). British MP Roger Gale said, "The conditions are wholly unrealistic. They are saying they are going to practice their safety procedures, but without fire or the emergency services. They know exactly what is going to happen. The problem two weeks ago was that people were evacuated, but they were lying on the floor choking."

In the Mont Blanc fire, 2 people died in the fire shelters due to smoke inhalation. Five firefighters used a shelter - one of them (Chief Tosello of the Chamonix fire department) died of a heart attack, triggered by smoke inhalation, after they were forced to share breathing apparatus (www.mrtunnel.com/page3.htm). Some of the injured people after the Tauern crash were in shock, crying and screaming. Other types of injuries include burns, injuries sustained during a crash, and crushing/trampling. In Baku, 245 of the fatalities were found inside the train, "most of them either squeezed or stamped to death" and 40 of them were found in the tunnel. However 95% (i.e. 760) of the persons who managed to evacuate the train survived. An alternative account ((www.mndaily.com/daily/1995/10/30/world_nation/wn30aa.ap/) puts the fatalities down to carbon monoxide poisoning – probably the truth lies somewhere in between these two extremes.

Injuries due to jumping from a moving vehicle (Gray & Varkevisser, 1995) were rare (the Cairo fire occurred outside, not in a tunnel). There were also no accounts of people being hit by moving vehicles, although fear of this happening dissuaded the controller at Kaprun from moving the train back out of the tunnel (www.funimag.com/funimag18/Funimag-Kaprun03.htm) (which with hindsight would probably have saved most if not all of the victims). First aid may be required by many of the victims, but this will be administered in a “safe” place, so will be outside the domain of interest for the evacuation process.

1.6.8 Summary of Human Behaviour in Tunnel Fires

Overall, behaviour patterns are not dissimilar to other building fires, although the tunnel fire environment may become severe more rapidly thus cutting down on some of the options.
As far as behaviour modelling for risk assessment purposes is concerned, only the more severe fires need to be considered. The probability of a severe fire, as opposed to any tunnel fire, can be estimated from statistics. The riskiest fires will be characterised by rapid fire growth, and rapid smoke spread. People will frequently be exposed to smoke at some stage, and when they are the visibility will be almost zero.

As in building fires, a person's role has a major effect on the behaviour they will exhibit. In tunnels, the roles can be generalised to include members of tunnel staff, members of the rescue and emergency services, other members of staff (eg. train or bus crew), and members of the public. The main effects of role on behaviour are that:

- Members of the public tend to wait for information, rather than investigate to seek it out. People in authority may investigate before undertaking positive action.
- Members of staff may search and warn/rescue others, whereas members of the public only warn/rescue on an impromptu basis if they discover someone in need. They may also assist others to cross obstacles (eg. to get off a train), and then escape independently when they have done this. Moving through train doors may be very time-consuming, as may opening the doors in the first place.
- Disabled people may either have helpers with them, or may receive impromptu assistance; in either case, their capabilities may not be quite so restricted (although the able-bodied helper may be slowed down for a time).
- Members of staff may attempt to fight the fire, members of the public are less likely to. However if only "serious" fires are being considered, it may be assumed that all attempts fail in these cases.
- Members of staff will attempt to control the evacuation by giving orders, directions, etc. Members of the public are less likely to do this, and more likely to be ignored if they try.
- Members of the public can only communicate face-to-face. Members of staff can communicate at a distance (eg. by radio amongst themselves, or by P.A. to members of the public) - as long as the system is still working.

Procedures in control rooms may break down under the stress of trying to manage the incident. Members of staff may also fail to behave as trained. Breathing apparatus may not be worn, thus preventing a member of staff from carrying out his required duties.

Group formation occurs, as in other building fires. Drivers are extremely reluctant to abandon their vehicles - there may be a number of "good" reasons for this. People are also extremely reluctant to abandon their luggage, and will take it with them if possible when evacuating public transport. Luggage in private vehicles will be left behind when the vehicle is abandoned. (Small items may be taken, which would have no effect on the evacuation)
People will prefer to leave by the tunnel portal - the "familiar" route. Emergency exits will only be used if people are exposed to smoke, and even then may not be noticed. People will not be able to go past the fire,

except perhaps at the earliest stages. If there are "authority figures" giving directions, these will involve moving away from the fire, rather than attempting to get past (to a nearer portal).
People will try to run, but require flat ground and adequate visibility to achieve this - which will generally not apply, especially later in the fire. Most people will only be able to run for short distances anyway. For modelling purposes, conservative results will be obtained if people are assumed to move no faster than normal walking speed (and much slower, when in smoke).

1.7 Literature review of egress modelling

1.7.1 Overview

Safe means of escape in fire and other emergencies is a principal requirement for design and operation of buildings and transport systems.
The time required for escape (RSET) is an essential part of performance-based fire safety design. Once a general warning has been given to the building occupants, evacuation commences with a series of initial behaviours (the pre-movement time) followed by movement into and through escape routes (the travel time). Also important are the interactions between pre-movement and travel behaviours for all individual occupants.

Numerical models of the evacuation process vary widely in their degrees of sophistication. At the simplest level there are engineering design tools that treat evacuation by analogy with fluid flow in pipes. At the other end of the spectrum there are extremely detailed models of the behaviour of individual people. As with all models, there is no right or wrong approach, since this depends on the intended application. Nevertheless, there are a number of advantages to the more sophisticated models.
The detailed behavioural models make all the complexities explicit. This is a great advantage when seeking to understand why the model gives the results it does. With simpler models, the answer is more likely to be “because that’s the way the model works”.
Detailed models are closer to “first principles” and may be easier to apply in novel circumstances. (Consider a comparison between CFD models and zone models for smoke movement; CFD models can deal with far more complex compartment geometries for example)

The CRISP model (Fraser-Mitchell, 1994, 1996, 1997, 1998, 1999, 2000, 2001; Boyce & Fraser-Mitchell, 1998) is a Monte-Carlo simulation for fire risk assessment. However it incorporates a detailed behaviour model rather than something simpler which would run faster. Why? The justification is that the risk assessment is based on fractional effective dose (FED), and accurate FED estimates require accurate exposure times. Therefore the behaviour model needs to predict where people will go, and how long they will spend in different areas (rooms) of the building.
The disadvantages of detailed models are that they expose the users to daunting levels of detail, and that in some aspects the necessary data values are unknown (requiring sensitivity studies to understand the consequences of different possible values).
The single most important feature which all the models examined in this survey lack is a convincing battery of validation comparisons. In most part this is due to a general lack of data suitable for validation purposes. The variability of human behaviour compounds this problem, making repeatability of experiments an issue. Until a systematically graduated approach to validation is adopted by the international fire safety community, this will remain the single most important issue for the development and wide-scale acceptance of evacuation models.

1.7.2 Standard Features of Evacuation Models

Type of Application

Most of the models covered by this survey are simulations of the evacuation process. However, a few are optimisation models, that calculate the minimum time in which a building (or other enclosure) could possibly be evacuated. Any time delays other than due to unavoidable congestion are ignored, thus the evacuation time is thus purely dependent on the physical flow processes, and the number of people using each exit path is optimised to minimise the time.
The optimisation models tend to be those catering for large numbers of people or where the occupants are treated as a homogenous ensemble.

Geometrical Representation

Building geometry can either be described by a coarse network (each node typically represents one room or corridor) or a fine network (each node is typically a 0.5m square "pixel").
In a coarse network, the size and shape of each node is not considered, except to define the maximum number of people that may occupy each node, and the length of time required to travel from one node to another.

In a fine network, representation of the detailed compartment geometry, internal obstacles and the location of individual people becomes possible. The movement of people can be influenced by such factors as overtaking others, obstacle avoidance, etc.

Fine networks are necessary to calculate complex flow rates (eg. merging or contra-flows) from first principles, coarse networks would require empirical equations. The more "homogeneous" the population behaviour, the less distinct the difference between coarse and fine networks (ie all flows heading to exits, no contraflows & limited merging).

People Representation

The simplest models treat the population as a homogeneous fluid, or mindless particles (“ball-bearings”), and concentrate on the flow capacity of the building. At the other extreme there are detailed simulations where each person is treated individually, with explicit behavioural rules.

In this category the models tend to form a continuum rather than two discrete alternatives. For the purposes of simplifying the survey however, it has been assumed that the representation is either “global” (fluid, or “ball-bearings”) or “individual” (capable of response to stimuli).
In some cases the movement model may be very detailed, with each “particle” (person) treated separately and given individual attributes (such as initial reaction delay time, and unimpeded walking speed), yet the behaviour is very simple (“head for the nearest exit”). These cases are included in the “global” group. In other cases behaviour may be a little more complex, with each person assigned a preferred (or “hard-wired”) exit choice. These cases are classified as the “individual” category, as of course are those where even more complex behaviour (eg. investigate, search the building, warn / rescue others, etc) is considered.

Human Behaviour

Human behaviour is the most complex and difficult aspect of evacuation to simulate, yet is crucial to accurate results. This could be classified according to the type of algorithm employed but a somewhat simpler and more useful approach is to consider what types of behaviour are considered rather than the details of the calculation. Obviously the choice of certain types of algorithm will preclude various aspects of behaviour. For example, if the algorithm is based on an analogy with Physics: “ball-bearings” rolling

“downhill” to an exit, then the “gravitational field” will always lead the person to the nearest exit, and alternative exit choices are not allowed.
The simplest level (“egress only”) considers no other form of behaviour, apart from an abstract representation of “pre-movement” activities by a delay time for each occupant before they may start to move. The people may however be allowed some flexibility in exit choice.
The intermediate level (“fixed”) covers models where the occupants may have a number of tasks to perform before they are allowed to commence evacuation. However these tasks are usually carried out in a deterministic sequence.

The highest level (“adaptive”) also has occupants with a variety of tasks to perform, however the choice of task, and whether these are completed or replaced by alternative actions, is determined by the state of the environment, actions of other people encountered, etc. Adaptive behaviour models are potentially the most realistic, since the complexities of human behaviour are made explicit and amenable to users’ control (rather than reflecting the original program developer’s perceptions in a hard-wired algorithm).

Because of the complexity of behaviour, no model to date addresses all the identified behavioural aspects of evacuation. Furthermore not all of these aspects are even fully understood or quantified.
Although each person’s decision process is modelled separately, this does not preclude the option for co-operative or group behaviour. For example a person may have a task to rescue a dependant person; the dependant person may wait to be rescued. However when the rescuer meets the dependent, the task of both may change to “escape”, and the movement process modified to keep the pair together.

Interaction between People and Smoke

The intended use of the evacuation model will determine whether there is any consideration of the effect of smoke on the evacuation process. For many fire safety engineering designs, the objective of the design is to maintain a clear means of escape for as long as necessary. In such cases the model is used merely to determine the length of time required, and it is assumed that any protection systems function as designed so that smoke is not an issue during the evacuation. All of the “optimisation” models and many of the “ball-bearing” models are used in this fashion.
Other models do not allow the presence of smoke to influence behaviour, but do calculate the effects of smoke toxicity. This may actually take place outside the movement model per se, with each person’s evacuation path x(t), y(t) (and z(t) for multi-storey buildings) used as inputs to an integration of Fractional Effective Dose (FED) along the various paths. The success or otherwise of the design is then based on the FED’s accumulated by the occupants. By considering the probability of various different fire scenarios, occupant starting positions and other attributes, etc, a risk assessment becomes possible.
The ultimate realism requires that occupants may respond to smoke as they do any other stimulus. Most models would calculate the distribution of smoke and then use this as an input to the evacuation model, defining when areas become untenable or impassable (or at least a deterrent that modifies exit choice). The only drawback with this approach is that the consequences of human behaviours on the movement of smoke are not considered. The most obvious example is the opening or closing of a door, which may have beneficial or adverse impacts, but in any case has changed the boundary conditions for the smoke movement model. If the smoke movement has been pre-calculated, it will no longer be appropriate from this point in the evacuation.

Distinctions in the impact of smoke on the evacuation process are not always as clear-cut as the above discussion would suggest. Some models allow smoke to block off exit routes as a function of time, but do not include FED calculations. People may be allowed to seek alternative routes, or may simply be “trapped” when their preferred route is blocked.

Exit Choice

Optimisation models assume that each exit will be used by precisely the right number of people in order to minimse the overall evacuation time. Clearly this does not happen in reality. The “evacuation time” calculated by such models should therefore be recognised as a fairly abstract performance measure of the building, and no more.

In many cases, people will use the nearest exit available. This clearly minimises the amount of time any individual will spend in walking to the exit. However it may lead to some exits being more heavily used than others, and thus taking longer to discharge people through them.

“Heading for the nearest exit” is not a correct representation of human behaviour, since they may not be aware of the existence of some exits. It is thus more accurate to say they will head for the nearest familiar exit – even to the extent of ignoring indicated fire exits. This applies particularly to buildings where the occupants are not well acquainted with the layout, indeed where their knowledge may be restricted just to the route they took to their current location. Some models will incorporate this aspect of behaviour by giving different individuals a “hard-wired” exit to represent their familiar route. Again this will lead to some exits being more heavily used than others. There is a danger in using the model in this mode, in that the results will be heavily dependent on the numbers of people programmed to use each exit. Some form of sensitivity analysis to check the effects of these initial assumptions should be performed.

In reality, people in a fire will estimate how much time they have to perform various tasks before evacuation (this estimate may be wildly inaccurate). Part of this estimate will account for the perceived spread of the fire and smoke, and part will estimate the time required to escape. The perceived time required for escape will depend on the route chosen (unfamiliar exits will not be considered among the options), numbers of people heading for exits and the speed they can move at, etc. The preferred route will be the one that minimises the perceived time required. The choice of route may be revised as other circumstances come to light (eg. the initial choice is found to be blocked by smoke, so if there is another option that may be chosen instead). This process is modelled by “adaptive” exit choice, ie one that depends on all the other time-dependent features of the simulation environment.

Destinations

A convenient representation of human behaviour may be thought of as a sequence of “actions”, where each action requires the actor to go somewhere, and then do something (that takes time but does not require further movement). The types of destination required will therefore depend on the complexity of the behaviour model. As we have already discussed, for many models the only type of destination is an “exit”. This may be a route to the “outside”, or a sequence of doors from individual rooms, eventually leading to a final exit.

In order to represent more detailed behaviour (without employing a fully-detailed adaptive model), people may be required to visit an area (room) or sequence of such areas, before they are allowed to evacuate. This can enable possible problems with contra-flows (for example) to become apparent, and also whether the pre-escape activity is particularly detrimental to the actor’s survival chances.

In the most sophisticated models, the choice of destination is adaptive, depending on the particular action being undertaken, and may include individual people as well as appropriate rooms. Consider how this might work for a person searching a building (or part of a building). Rather than following a hard-wired sequence of rooms to visit, the person’s next room to search would depend on the proximity of rooms not previously searched, and maybe anticipate the actions of other searchers. If certain rooms became inaccessible due to the spread of smoke, these would drop out from the list of options for the next room to visit. Note that a hard-wired search pattern may well be more efficient in the absence of smoke, but is too inflexible to apply in all circumstances.

1.7.3 Survey of Evacuation Models

40 different models have been reviewed using the public-domain literature. It should be noted that few of these are commercially available. Most of the recent models are still undergoing development in a research environment. Many of the older models are no longer supported. The most recent direct reference (i.e. by the model developer, rather than a third-party user) is given as an indication of the model's vintage.

The models (see Table 1-5) have been classified according to the categories discussed above. In some cases it is not clear what the classification should be (particularly when trying to discretise a continuum); a "+" sign indicates the minimum appropriate classification. Generally, the higher the number in a given category, the more sophisticated and "realistic" the treatment of that aspect of evacuation. Overall, more recent models are more sophisticated. This is undoubtedly due to the increase in computer power over the years which makes more complex models feasible. There has been a time lag (of about 5-10 years) in the recognition of the importance of human behaviour in fire, and the ability to model it.

Table 1-5: List of model references.

AEA Egress
Ketchell, Cole & Webber (1993)
Ketchell (2001)
Ketchell, Bamford & Kandola (1995)

ASERI
Wenkman, Lehtimaki & Mannikko (1998)
Schneider (2001

BFIRES-II
Kendik (1985)
Stahl (1982)
Watts (1987)

BFSM
Watts (1987)
Fahy (1993)

BGRAF
Ozel (1992)

CRISP
Fraser-Mitchell (1994)
Fraser-Mitchell (1996)
Fraser-Mitchell (1997)
Fraser-Mitchell (1998)
Fraser-Mitchell (1999)
Fraser-Mitchell (2000)
Fraser-Mitchell (2001)
Boyce & Fraser-Mitchell, 1998

Donegan's Entropy Model
Donegan, Pollack & Taylor (1994)
Donegan & Taylor (1998)

Ebihara
Ebihara, Ohtsuki & Iwaki (1992)

EESCAPE
Friedman (1991)
Kendik (1985)

EMBER
Watts (1987)

ERM
Watts (1987)

E-SCAPE
Reisser-Weston (1996)

EVACNET+
Kendik (1985)
Watts (1987)
Kisko & Francis (1985)
Taylor (1996)

EVACS (Takahashi)
Takahashi, Tanaka & Kose (1989)

GridFlow
Purser (in press)

Helbing
Helbing, Farkas & Vicsek (2000)

Kakegawa (Ebihara)
Kakegawa, Yashiro, Ebihara & Ohtsuki (1994)

Klote Elevator Model
Klote (1993)

Kostreva
Kostreva, Wiecek & Getachew (1991)
Kostreva (1994)
Kostreva & Lancaster (1998)

Legion / Myriad
Still (2000)

Lo (SGEM)
Lo & Fang (2000)

MagnetModel
Okasaki & Matsushita (1993)

Mutani
Mutani & Cali (1998)

O'Leary
O'Leary & Gratz (1982)

Pathfinder
Cappuchio (2000)

PAXPORT/Pedroute
Barton & Leather (1995)
Bulman & Clifford (1995)
Buckmann & Leather (1994)

SEVP
Curtat (1998)

Simulex
Thompson & Marchant (1993)

Friedman (1991)

EvacSim
Poon (1994)
Poon (1995)
Poon (2000)

EXIT89
Fahy (1991)
Fahy (1993)
Fahy (1994)
Fahy (1996)
Fahy (1998)
Fahy (2001)

EXITT
Levin (1989a)
Levin (1989b)

Exodus
Galea & Perez Galparsoro (1994)
Owen, Galea & Lawrence (1997)
Galea, Gwynne, Owen, Lawrence & Philippidis (1998)
Gwynne, Galea, Owen, Lawrence & Philippidis (1999)
Gwynne, Galea, Lawrence & Philippidis (2001)

FEES/MB
Watts (1987)

FIRESCAP
Feinberg & Johnson (1998)

Wenkman, Lehtimaki & Mannikko (1998)
Thompson & Marchant (1994)
Thompson & Marchant (1995a)
Thompson & Marchant (1995b)
Thompson, Wu & Marchant (1996)
Thompson, Wu & Marchant (1997)
Olsson & Regan (1998)
Ashe & Shields (1998)
Kennedy, Harvey & Li (2001)

STEPS
Newman, Rhodes & Locke (1998)
Rhodes (1999)
Andersson, Hedskog & Nyman (2002)

Toshiyuki
Toshiyuki (1993)

TRAFFIC
Powell & Grubits (1999)

VEGAS
Still (2000)
Still (1993)
Judge (1993)
Geake (1993)
Still (1994)

Wayout
Shestopal & Grubits (1994)

Yoshida
Yoshida (1995)

Model Name / Author	Application	Geometry	People	Behaviour	Smoke	Exit Choice	Destinations	Latest ref.
AEA Egress	2	2	2	1	0+	2	2	2001
ASERI	2	2	2	0+	1	1+	1+	1996
BFIRES-II	2	1	2	0+	2	3	1	1982
BFSM	2	1	2	1	1	2	1+	1993
BGRAF	2	2	2	1+	0+	1+	1+	1992
CRISP	2	2	2	2	2	3	3	2002
Donegan's Entropy Model	1	1	1	0	0	0	1	1994
Ebihara	2	1	1+	0+	2	1	1	1992
EESCAPE	2	1	1	0	0	1	1	1985
EMBER	2	1	1	0	0+	1+	1	1982
ERM	2	1	2	1	0	1	2	1985
E-SCAPE	2	1	1	0	0	2	1	1996
EVACNET+	1	1	1	0	0	0	1	1996
EVACS (Takahashi)	1	1	1	0	0	0	1	1989
EvacSim	2	1	2	2	2	3	3	2000
EXIT89	2	1	1+	0+	2	2	1	1997
EXITT	2	1	2	2	2	3	3	1988
Exodus	2	2	2	2	2	3	3	2002
FEES/MB	2	1	1	0	0	1	1	1985
FIRESCAP	2	2	1	0	0+	1	1	1997
GridFlow	2	2	2	0	1	2	1	2000
Helbing	2	2	1	0	0	3	1	2000
Kakegawa (Ebihara)	2	2	2	1+	1	2+	3	1994
Klote Elevator Model	1	1	1	0	0	0	1	1993
Kostreva	1+	1	1	0+	0+	3	1	1998
Legion / Myriad	2	2	2	0+	0+	2+	1+	2002
Lo (SGEM)	2	2	1	0	0	2	1	2000
MagnetModel	2	2	1	0	0	1	1	1993
Mutani	1	1	1	0	0+	0	1	1997
O'Leary	2	1	1	0	0	2	1	1982
Pathfinder	2	2	1	0	0	1	1	2000
PAXPORT/Pedroute	1+	1	1	0	0	2	1	2001
SEVP	1	2	1	0	0	0+	1	1998
Simulex	2	2	2	0	1	2	1	1998
STEPS	2	2	2	0	0+	3	1	2001
Toshiyuki	2	2	1	0	0	2	1	1993
TRAFFIC	2	1	1	0	1	1	1	1999
VEGAS	2	2	2	0+	2	3	1	1993
Wayout	1	1	1	0	0	2	1	1994
Yoshida	2	2	1	0	0	0	1	1995

KEY TO NUMERICAL CODES

Application	1=optimisation, 2=simulation
Geometry	1=node, 2=mesh
People	1=global, 2=individual
Behaviour	0=none, 1=fixed, 2=adaptive
Smoke	0=none, 1=FED, 2=adaptive
Exit Choice	0=optimised, 1=nearest, 2=hardwired, 3=adaptive
Destinations	1=exits, 2=areas, 3=people

1.7.4 An Example of a State-Of-The-Art Egress Model: CRISP

CRISP (Computation of Risk Indices by Simulation Procedures) is a Monte-Carlo model of entire fire scenarios. The sub-models representing physical 'objects' include rooms, doors, windows, detectors and

alarms, items of furniture etc, hot smoke layers, and people. The randomised aspects include starting conditions such as various windows and doors open or closed, the number, type and location of people within the building, the location of the fire and type of burning item.
The basic structure of CRISP is a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behaviour and movement. All the physical 'objects' are supervised by the Monte Carlo controller, making each one perform for each time step. The Monte Carlo controller also handles all the input and output, initialisation for each run, and starts each run automatically. Functions are included to generate random numbers from any distribution. The calculations for each run are carried out iteratively, with variable time intervals to ensure the program's efficiency, accuracy and stability.

Smoke moves between rooms by means of vent flows, driven by pressures arising from buoyancy differences. The geometry of the room determines how quickly a growing smoke layer will descend. Combustion products are transported between the various cold air and smoke layers by plumes and vent flows. Heat may also be lost by radiation and conduction through the walls of the compartment.
Vents are defined as doors and windows, or any other opening which smoke may move through. They may open or close during the simulation as people move through them. However, doors can be specified as self-closing. The traversal difficulty includes physical and psychological aspects.
People are assumed to adopt distinct behavioural roles, either naturally or due to training. Their behaviour can be described in terms of actions, which may be abandoned, and substituted by new ones, depending on the state of the environment. Rational decisions are made based on current knowledge (which may be limited and/or incorrect). People never ‘panic’ (in real life, ‘panic’ behaviour is actually extremely rare).

Movement of people through a building firstly requires a route to be planned through the network of rooms. The choice of route is influenced by the doors' transit difficulty (modified for the presence of smoke) and the distance. Within each room, movement to the next door on the route is directed by means of a ‘contour map’ of distance to go. This enables any obstacles to be avoided. Movement speed is affected by local crowd density. Deviations from the minimum distance path through a room may be made to avoid areas of high crowd density.

The model attempts to calculate ‘pre-movement time’ (rather than use an empirical distribution) in terms of the time delays associated with various actions performed by the occupants in response to the early fire cues. The occupants may perform a number of actions (eg. investigate, warn others) before actually starting to escape (thus the term ‘pre-movement time’ is not strictly accurate). If the occupant’s ‘pre-movement’ actions do not actually require him to move, then all these actions can be lumped into a single delay in reacting to the alarm.
As the people move around, they are exposed to smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is assumed to be ‘dead’. The risk is expressed simply in terms of the fraction of people originally present who end up ‘dead’, averaged over a sufficiently large Monte-Carlo sample.

CRISP has a number of ‘switches’ which control how the program operates. One of these allows the model to run in evacuation mode, without simulating the fire or calculating toxic exposures. All the building occupants are assumed to be alerted at the start of the simulation. Once they have finished reacting, their full set of behavioural rules governs what they do next. A number of actions are only relevant in the presence of fire or smoke but can still be applicable if the fire is only implicit.
Clearly the standard metric for comparison of runs (risk of death) will not be applicable when there is no fire. However the model also calculates detailed statistics of the evacuation process. At the most basic level, there is the time required to clear a given proportion of the initial population (eg. 25%, 50%, 75%, 95%, 99%, 100%) from the building. It is also possible to determine when particular regions of the building have been cleared, and how long people from different starting points take to evacuate. At the finest level of detail, it is possible to monitor the flow rates at every doorway in the building.

Interpretation of the evacuation results may simply involve comparing the time for the building to become empty with some target time. Alternatively a fire model may be used to predict when regions of the building become untenable, and the evacuation results checked to confirm that nobody is inside or subsequently enters an untenable region. Where rooms are particularly large or complex in shape, a CFD model (eg. the BRE fire model JASMINE) is more likely to give accurate results for smoke flows, temperatures, etc, than CRISP's own internal fire model (because the zone model approximations may not be appropriate in a complex geometry).

The drawback to using an external fire model is that, as far as the evacuation process is concerned, there is no fire or smoke to respond to. However there are ways to implicitly include the fire in a rather abstract way (rather than the explicit representation employed in the full risk assessment mode). The transit 'degree of difficulty' for some doors can be set to a higher value than normal, to discourage or prohibit the entry of people into certain regions of the building (thus representing the presence of smoke). The behavioural rules followed by the people can also be modified to implicitly recognise the presence of a fire. For example, people in the vicinity of the fire may be given rules to enable them to react more quickly than those who are more distant. The more distant people could then react once warned by people who have already reacted, or they could remain inactive, waiting for a predetermined period (by which time a general alarm could be assumed to have been activated) before reacting.

1.7.5 Model enhancements required to simulate behaviour in tunnel fires

Most of the models surveyed have not been used for tunnel or underground stations applications, although there have been a few exceptions (Kennedy, Harvey & Li, 2001; Rhodes, 1999; Andersson, Hedskog & Nyman, 2002). In these exceptions, it has been assumed that the movement of people has not been impeded by smoke - the objective of the fire engineering design being to keep the means of escape clear for long enough to allow the people to leave. As we have seen from chapter 4, this assumption may not always be realistic. CRISP has been used to simulate a tunnel fire, but this was only a demonstration of the model's capability rather than a serious study (Fraser-Mitchell, 2003). It did however include a growing fire, spreading smoke, and people interacting with the smoke.
The various characteristics used to categorise the models surveyed are now discussed in terms of the requirement to simulate tunnel fires.

- Type of application - must be a simulation
- Geometry representation - needs to be a fine mesh, so that effects of constriction due to slow moving people (possibly assisting others, or carrying bulky luggage), can be simulated.
- People - must have individual characteristics. The actions of members of staff can significantly affect the outcome. Different roles must be modelled.
- Behaviour - must be adaptive. People need to respond to changes in the environment, whether this is other people giving instructions, or smoke building up, etc. As people tend to wait for information (or for smoke to reach them), simplified behaviour - assuming that everybody reacts at the same time, for instance - may not give realistic or even conservative results.
- Interaction with smoke - should be adaptive. People may not start reacting until they are exposed to smoke, for example. Ideally the smoke movement calculation would be fully coupled with the evacuation model (as in CRISP), but a pre-calculated smoke distribution would also suffice for most scenarios. Some thought might need to be given to how long people could remain in a railway carriage after the first door (or window) has been opened, for example, if the smoke is pre-calculated.
- Movement speed need not exceed normal walking speed (running unlikely to be feasible), but should be reduced if a person is in smoke.

- Exit Choice - should be adaptive. It would be too optimistic to assume everybody would use the nearest emergency exit.
- Destination - needs to include other people, if the actions of members of staff are to be simulated properly.

Very few of the surveyed models fulfill all the above criteria. The CRISP and Exodus models appear to be the closest to the ideal requirement. However there are still some details to improve, namely:
People assisting others to cross obstacles - this may be possible to represent simply by introducing extra time delays for an able-bodied person in the vicinity of someone in need of help. In this case the assistance is implicit, rather than an explicit behaviour action.

- Disabled people - this needs to be done in more detail than simply assuming they move slower than other people. In particular, their response to initial cues may be different (if sensory disabled), and some aspects of movement may be much more awkward than others.
- Rescuing luggage - more research is required on the level of smoke, etc, that would inhibit this behaviour.

1.8 Conclusions regarding Evacuation

Overall, behaviour patterns are not dissimilar to other building fires, although the tunnel fire environment may become severe more rapidly thus cutting down on some of the options.

As far as behaviour modelling for risk assessment purposes is concerned, only the more severe fires need to be considered. The probability of a severe fire, as opposed to any tunnel fire, can be estimated from statistics. The riskiest fires will be characterised by rapid fire growth, and rapid smoke spread. People will frequently be exposed to smoke at some stage, and when they are the visibility will be almost zero.

As in building fires, a person's role has a major effect on the behaviour they will exhibit. In tunnels, the roles can be generalised to include members of tunnel staff, members of the rescue and emergency services, other members of staff (eg. train or bus crew), and members of the public. The main effects of role on behaviour are that:

- Members of the public tend to wait for information, rather than investigate to seek it out. People in authority may investigate before undertaking positive action.
- Members of staff may search and warn/rescue others, whereas members of the public only warn/rescue on an impromptu basis if they discover someone in need. They may also assist others to cross obstacles (eg. to get off a train), and then escape independently when they have done this. Moving through train doors may be very time-consuming, as may opening the doors in the first place.
- Disabled people may either have helpers with them, or may receive impromptu assistance; in either case, their capabilities may not be quite so restricted (although the able-bodied helper may be slowed down for a time).
- Members of staff may attempt to fight the fire, members of the public are less likely to. However if only "serious" fires are being considered, it may be assumed that all attempts fail in these cases.
- Members of staff will attempt to control the evacuation by giving orders, directions, etc. Members of the public are less likely to do this, and more likely to be ignored if they try.

- Members of the public can only communicate face-to-face. Members of staff can communicate at a distance (eg. by radio amongst themselves, or by P.A. to members of the public) - as long as the system is still working.
- Procedures in control rooms may break down under the stress of trying to manage the incident. Members of staff may also fail to behave as trained. Breathing apparatus may not be worn, thus preventing a member of staff from carrying out his required duties.
- Group formation occurs, as in other building fires.
- Drivers are extremely reluctant to abandon their vehicles - there may be a number of "good" reasons for this. People are also extremely reluctant to abandon their luggage, and will take it with them if possible when evacuating public transport. Luggage in private vehicles will be left behind when the vehicle is abandoned. (Small items may be taken, which would have no effect on the evacuation)
- People will prefer to leave by the tunnel portal - the "familiar" route. Emergency exits will only be used if people are exposed to smoke, and even then may not be noticed. People will not be able to go past the fire, except perhaps at the earliest stages. If there are "authority figures" giving directions, these will involve moving away from the fire, rather than attempting to get past (to a nearer portal).
- People will try to run, but require flat ground and adequate visibility to achieve this - which will generally not apply, especially later in the fire. Most people will only be able to run for short distances anyway. For modelling purposes, conservative results will be obtained if people are assumed to move no faster than normal walking speed (and much slower, when in smoke).

Most of the models surveyed have not been used for tunnel or underground stations applications, although there have been a few exceptions. In these exceptions, it has been assumed that the movement of people has not been impeded by smoke - the objective of the fire engineering design being to keep the means of escape clear for long enough to allow the people to leave. As we have seen from chapter 4, this assumption may not always be realistic. CRISP has been used to simulate a tunnel fire, but this was only a demonstration of the model's capability rather than a serious study. It did however include a growing fire, spreading smoke, and people interacting with the smoke.

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- Interaction with smoke - should be adaptive. People may not start reacting until they are exposed to smoke, for example. Ideally the smoke movement calculation would be fully coupled with the evacuation model (as in CRISP), but a pre-calculated smoke distribution would also suffice for most scenarios. Some thought might need to be given to how long people could remain in a railway carriage after the first door (or window) has been opened, for example, if the smoke is pre-calculated.

Movement speed need not exceed normal walking speed (running unlikely to be feasible), but should be reduced if a person is in smoke.

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- Disabled people - this needs to be done in more detail than simply assuming they move slower than other people. In particular, their response to initial cues may be different (if sensory disabled), and some aspects of movement may be much more awkward than others.
- Rescuing luggage - more research is required on the level of smoke, etc, that would inhibit this behaviour.

2. DRIVING BEHAVIOUR IN ACCIDENTS

E. Konrad, M. Polic & A. Sabadin
University of Maribor, Slovenia

2.1 Open road accidents

There are a number of theories and models explaining different aspects of drivers' behaviour in general (not specifically focussing on driving in tunnels). We shall present two of such models here, but it must be understood that both offer only partial explanation of phenomena. Also some empirical data about traffic accidents will be presented.

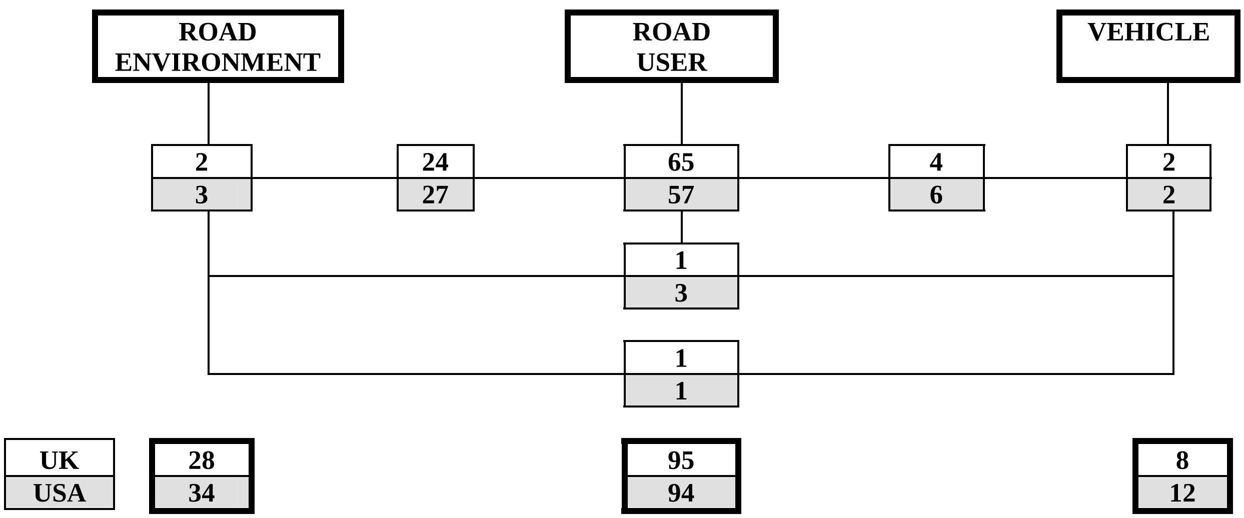


Figure 2.1: Contribution of different factors (in %) to traffic accidents, as independently revealed by studies in UK (white numbers) and USA (grey numbers) (Rumar, 1985). Connections between rectangles signify combination of factors, e.g. road environment and road users together cause 24 % of traffic accidents in UK and 27 % in USA, road users alone cause 65 % of accidents in UK and 57 % in USA, road environment and vehicle cause 1 % in UK and 1 % in USA, etc.

Shinar (1978) defined an accident as an unintended and unpleasant event, and in its broadest scope 'a*n unexpected not necessarily injurious or damaging event, that interrupts a completion of an activity; it is invariably preceded by an unsafe act or an unsafe condition or both, or some combination of unsafe act and/or unsafe conditions'*.

We may say that an accident happens whenever one or more factors, labelled as its cause, deviate from the norm to such an extent that the system cannot accommodate it. Accidents are usually caused by more than one factor. Accident causes could be classified as either *vehicular* (e.g. faulty brakes), *environmental* (e.g. glare, slick road) or *human* (e.g. misjudgement, improper response). The majority of studies are reporting a prevailing role of human factor in traffic accidents causation (Figure 2.1). Percents differ, but there are reports that road users themselves are responsible for more than 90 % of accidents, either alone or in combination with other factors, e.g. environmental. In the majority of accidents more factors are involved, usually human with some other(s), e.g. excessive speed and worn brakes or wet roadway.

We can distinguish *direct* and *indirect* human causes of traffic accidents, the former being behaviour and events that immediately precede the accident and are directly responsible for it (e.g. recognition errors, decision errors, performance errors, critical non-performance). Indirect causes are conditions or states (e.g. physical or physiological as alcohol impairment, mental or emotional as being in hurry, and experience or exposure as driver inexperience) whose presence impaired the driver's level of information processing functions.

We can view the accident as the end result of "*an accident process*" (Fell, 1976), in which causally connected events, conditions and behaviour are following each other. Usually we recognised only the last one in the chain as the cause of an accident, because it is the most apparent. To prevent an accident the chain must be broken as early as possible. Fell thus wanted to present the causal scheme of accidents. He emphasized mainly the human element. His system is built on the analysis of cause-effect relationships leading to an accident. The consequence is the basic error, non-performance, or behaviour leading into crash; the cause is the factor or event which is direct reason for the error, non-performance or behaviour.

Although the consequences of traffic accidents in tunnels may differ from those happening on the open road, their causes may in principle be similar. In general the most frequent driver errors are connected to recognition (55 %) and decision-making (50 %), the least frequent being the errors in reaction (10 %). This means that the majority of accidents are caused by deficient or erroneous perception of environment, by improper information processing, and only a minority by poor vehicle control. Some of the most frequent errors as revealed by Treat and his co-workers are (Shinar, 1978):

- *Improper Lookout.* Delayed recognition due to failure to perform an adequate visual search in a situation that requires a distinct visual surveillance.
- *Excessive Speed***.** Speed that is excessive relative to the traffic, roadway, and ambience conditions – regardless of the legal speed limit.
- *Inattention***.** Delayed recognition due to preoccupation with irrelevant thoughts or wandering of the mind. Most frequently drivers did not perceive that traffic flow in front of them stopped or slow down.
- *Improper Evasive Action***.** Failing to take an emergency action that is apparent and within the capabilities of an adequately trained an alert driver.

All the listed causes are also under the influence of the environment and could be changed with the changes in environment. Adequately constructed tunnels could support safety, while inadequately constructed ones could contribute to accidents.

We could not skip the psychological approach in discussing the traffic environment, because only in the human-environment interaction its advantages or deficiencies are expressed. Although we should not neglect human behaviour many recent findings[3] showed that environmental interventions that take into account lawfulness of the road users' behaviour could ensure greater traffic safety.

[3] These aspects are extensively discussed in a book edited by Fuller and Santos (2002). **Human Factors for Highway Engineers**, published by Pergamon.

Theories are necessary to treat a subject scientifically, in particular to structure data, check facts, create links to other fields of knowledge, or to explain or predict circumstances (Huguenin, 1997). As Geller (1996) suggested, without theory successful countermeasures are not possible, because, we could add, they would be similar to blind trials. Unfortunately we do not have a complete theory of human behaviour in general, and on drivers behaviour in particular yet. The topic is too complex to be explained by any of the current theories in its totality. They could only explain its particular aspects.

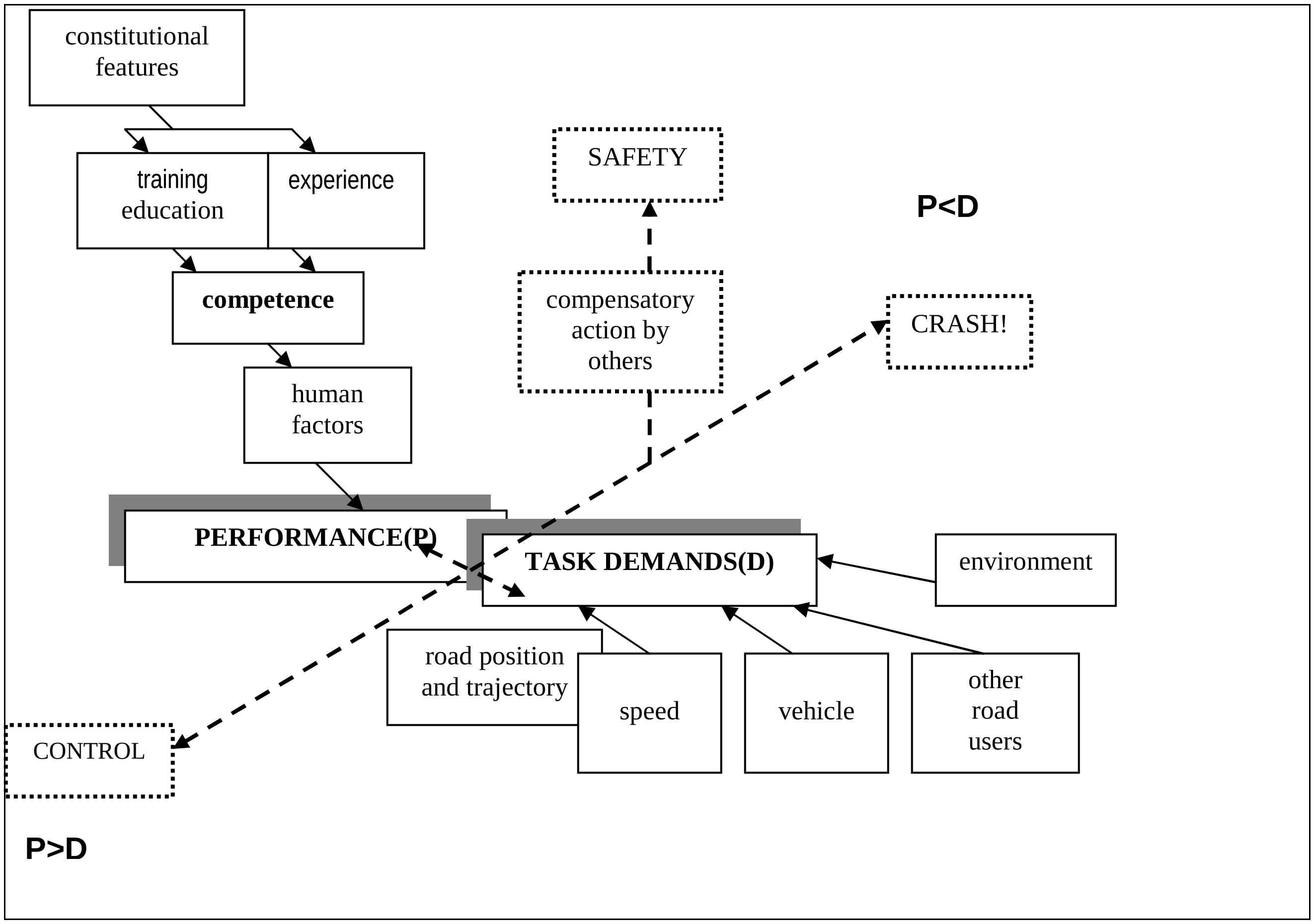


Figure 2.2: The Task-Capability Interface Model (Fuller & Santos, 2002)

Fuller and Santos (2002) proposed the task-capability interface model (Figure 2.2) of driving. They describe driving as a dynamic control task in which the driver has to select relevant information from the environment (mainly visual) to make decisions and execute appropriate control responses in order to achieve safe mobility. The key factors here are the environment, constituted by the roadway and physical conditions such as surface adhesion and visibility, other road users and the information display, control and operational characteristics of the vehicle. The driver himself provides two task elements: road position and speed. The driver brings to this task his constitutional characteristics, his knowledge, skills and competence. His performance in any moment will be affected by factors like fatigue, emotion, stress, distraction and drugs to produce his capability. Putting both aspects together we get a simple model of the interface between task demand and driver capability. If capability exceeds task demand then the driver will drive safely, if not crash or loss of control is implied. This is only a static picture and Fuller and Santos (2002) believe that for most of the time drivers drive so as to achieve their mobility and travel goals while ensuring that the *difficulty* of the task remains within acceptable limits, proposing in this way so called *task-difficulty homeostasis*[4] model. The dynamic interaction of the driver with the unfolding road and traffic scenario determines objective task difficulty and the perception of this is compared with the driver's target difficulty. Consequentially the driver is adjusting his driving to the desired level of difficulty. Implications of this approach are (Fuller and Santos, 2002):

- Safety may be challenged if there is a discrepancy between the driver's perceived task difficulty and objective task difficulty, such that the driver underestimates the real task difficulty;
- If a driver can increase speed without increasing perceived task difficulty, s/he will do so;
- Where conditions are such that the demands of the task exceed driver's capability, and he can do nothing to reduce those demands or enhance his capability, the driver will opt to avoid those conditions.

A potential design strategy might be to make the task appear more difficult than it objectively is (Fuller and Santos, 2002).

While driving, driver is processing information at least about three sorts of tasks (Riemersma, 1979):

- Maintaining the direction and control of speed;
- Manoeuvring (change of direction, overtaking) and
- Route choice.

While on the first, lowest level, the information processing could be completely *automatic*, on the higher levels it is *cognitive*. Ineffectiveness of traffic signs is often caused just by the fact that the information they are bringing interferes with automatic information processing and control of behaviour, e.g. in maintaining the direction and speed. The goal of this interference is just an *interruption* of the automatic behaviour. When this do not happen, traffic signs are ineffective. Many findings show that it is not easy to achieve change in automatic behaviour even when traffic signs are clearly visible and understandable.

Summala (1997) also considers the driver's task as a functional hierarchy, from the vehicle control level up to trip decision; as a functional taxonomy of behaviour; and at psychological processing level, believing that time and speed have a central role in traffic behaviour and behavioural adaptation at many levels. Brown (1982) is listing six driver's task connected to safety:

- *Route finding.* The driver is searching the road scene for symbolic or verbal road signs, signals or landmarks in order to proceed along the chosen course. Route finding requires him to make a continuous comparison of his mental representation with the actual road scene. Possible source of discrepancy between the actual traffic environment and the driver's mental map lay in the signs that do not conform to driver's expectancies (Figure 2.3). In tunnels, especially long ones, we would not expect these kinds of problems, as they are also an orientation tool.
- *Route following.* It concerns the behaviour of drivers passing through familiar environment. Their course and progress will normally be determined by recognition, often sub-consciously, of geographical and traffic system features. They will therefore not need to read road signs; their daily experience with their route will often lead to acceptance of tighter schedules; and they will thus tend to drive at higher speeds and be relatively intolerant of delay. It follows that they will be disconcerted by changes introduced into their familiar routes; e.g. stopped vehicle in a tunnel.
- *Lane tracking.* Drivers have to perform a tracking task as they steer their vehicle along the chosen route. The visual demands of steering will naturally be a function of the physical environment, vehicle design, traffic conditions, speed, etc. Source of visual information on

[4] Though his idea reminds us to Wilde's risk homeostasis model, there is difference in target: task difficulty vs. risk.

which drivers steer their vehicles will often be remote, in terms of visual angular displacement. Drivers on the straight course will fixate in the region of the 'focus of expansion': that is where objects appear stationary and will tend to bias their horizontal scanning fixations towards the opposing stream of traffic.

- *Collision avoidance.* This is continuous demand on the driver. Attention, perception and decision –making will therefore continually be occupied by the detection, prediction and resolution of dynamic interaction between a driver's own course and those of other road users. There will be three different determinants of the driver's visual scanning for collision avoidance cues: (a) attention will be drawn to unusual and compelling events which require a decision regarding their hazard potential; (b) attention will be directed to those parts of the road scene which are expected to produce hazard; (c) events for which a decision has already been made will need to be checked for evidence of the decision's appropriateness.
- *Rule compliance.* The duties and responsibilities of the driver are defined by legislation and convention. Many of these rules will be memorized and brought into operation by features and events perceived in the road scene. Others will be signalled by a variety of road signs, containing more specific messages. The latter more imperative type of communication, if well designed, will usually not increase the information-processing load of the driver unduly. It may create frustration among road users if rules are not compatible with the driver's perception of immediate road safety needs. A problem with many rules is that they are designed for 'average' or sometimes 'worst case' situations and individuals. A common example is a speed-restriction which applies regardless of traffic conditions.
- *Vehicle monitoring.* Experienced drivers will continually monitor information on the state of their vehicle. Many of these monitoring activities are carried out subconsciously, or are so over-learned that they minimally distract from the main task of scanning the road scene.

Rumar (1991) proposed a simple model of the driver that takes into account certain perceptual limitations. Rumar’s model shows us how stimuli from the environment influence different senses, and the sequence of filters determines what type of information will be used and what will not. Only the most important part of the information will pass limited channel and become the external basis for decisions. At the end muscles perform intended action that changes the stimuli and gives feedback to perception. These basic functions are under the influence of some higher functions, e.g. the motivation. The motivation and experience influence the level and direction of attention and expectation. Three filters present characteristic limitations, that are possibly leading into errors, unwanted behaviour and finally to accidents.

Physical filters are given by the nature of the environment (e.g. barriers for the view, noise) and should be removed to enable driver to perceive and estimate the situation.

Perceptual filter is depending mainly on physiological limitations. We need certain low (threshold) quantities of energy, certain smallest differences between them, in order to perceive or distinguish them. Activation of this filter is evident during the night drive, when perceiving the speed of approaching vehicles or of our own vehicle.

Cognitive filter is more depending on motivation, experience and expectations. Its activity is evident in perception and influence of traffic signs, in anticipation of movement of other vehicles, in estimation of danger, acceptance of safety measures, etc. Drivers perceive and remember traffic signs according to their subjective importance. We must be aware that simultaneously at most two traffic signs are effective. If there are more of them on certain place they will only contribute to driver's overloading.

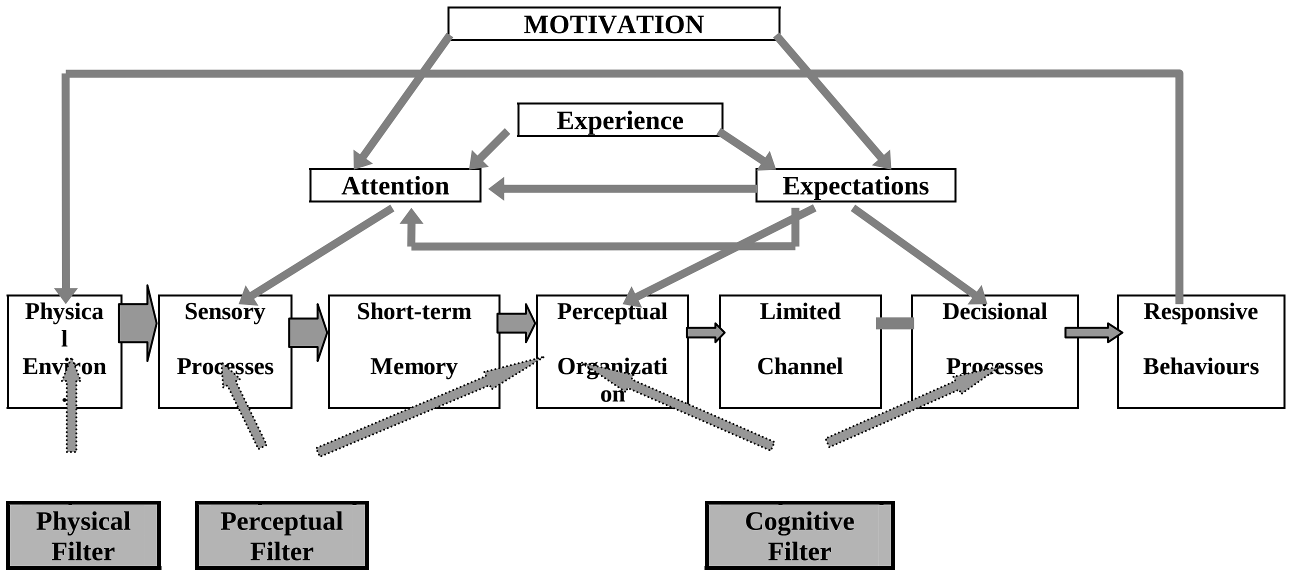


Figure 2.3: Rumar's (1991) model of driver behaviour, describing the main factors determining acquisition and processing of information. Three filters are pointing to three characteristic errors.

Some countermeasures based on this model may be:

- Adaptation of the environment to human limitations (e.g. road lighting, emergency lane)
- Acquainting road users with these limitations and adequate training
- Enabling feedback that usually traffic is not offering
- Changing drivers' values and attitudes toward traffic safety.

However, it is not so simple to use practical countermeasures based on this model. Probably the most easy countermeasure to implement is to provide feedback that the driver normally would not have (this will also be done in the driving simulator studies). A problem with calamities in tunnels is that they happen so seldom that it is not something that road users expect and with which they have experience.

2.2 Risk, warning and driving behaviour

Though pretty much is known about causes of accidents, countermeasures are still not sufficiently efficient. What are the reasons that drivers do not properly respond to warning messages? Why do drivers not behave according to traffic rules that assure greater safety on the roads? Are they not aware of risk or is the risk not important to them? Perhaps we could agree with Lehto (1998) when he mentioned that a new perspective on hazard communication places less emphasis on perceptual issues emphasized in the past (e.g. legibility, contrast, or conspicuity) but more on measuring and predicting comprehensibility, risk perception, and behavioural propensities as a function of factors such as message length and explicitness, user experience, cost of compliance, and past behavioural patterns. Edworthy (1998) believes that people will decide whether or not to comply with a warning – or more generally, to show safety behaviour – if the perceived benefits of compliance appear to outweigh the costs. A person confronted with the hazard is weighing the potential benefits of appropriate safety behaviour against the costs that might be incurred in doing so. They are thus making a utility judgment which presents a cost-benefit analysis informed by the cues coming from the hazard, the individual, and from other sources. Here we are also facing the problem of risk communication (e.g. warning, traffic sign), namely the perception and interpretation of risk. There are numerous biases connected to risk, e.g. scale compression, underestimation of risk associated with familiar activities, optimism bias[5] (= tendency for people to give lower risk estimates for themselves than for others), etc. Nevertheless - contrary to expectations - research evidence (Ayres et al., 1998) suggests that behavioural choice is not closely related to subjective risk. There are other considerations that are more important, e.g. pedestrians make riskier street crossings if it is raining. It seems that often the costs of compliance with the warning or safety rule influence whether people will comply with them. It must be also mentioned that the inter-subject variability in risk perception is too high to provide a reliable basis for rational decisions and to reliably predict differences in behaviour (Ayres et al., 1998). Then why does this gap exist between behaviour and perceived risk? Ayres et al. (1998) offers three possible explanations:

- **Attitudinal explanation**. In an effort to account the failure of many warnings, Lehto (1991) adopted Rasmussen's (1995) three level behaviour model (skill-, rule-, and knowledge-based behaviour) and added a fourth level for judgment-based behaviour (i.e. influence of beliefs and attitudes). Intervention at one level will unlikely produce desired changes at other levels. Perceived risk will probably be utilized in decision making at the knowledge-based level, and is less likely to influence behaviour originating from skill-based or rule-based levels. At the judgment-based level, preconceived notions of the risk or acceptability of an activity can interfere with rationality of decision making. At this level it is more important to persuade than to inform (Lehto, 1991). Additionally, some degree of risk can be attractive and even exciting. So people may share the same assessment of perception of the risk associated with a proposed activity, but may differ in the level of acceptable risk. Also perceived risk could be regarded as less important than other considerations.
- **Biases**. As already mentioned there are some inaccuracies in subjective risk assessment (i.e. ignoring small probabilities, considering only short term risks, optimism bias, poor judgement of personal susceptibility, overestimation of personal control over activity, etc.) influencing safety behaviour.
- **Irrelevance**. While previous explanations propose reasons why risk perception may play only limited role in influencing behaviour, they are consistent with the claim that risk perception is irrelevant to most common behavioural decisions. According to this view most common risk taking is nondeliberate, i.e. we are not thinking about risk while driving.

But if risk perception is inaccurate or even irrelevant, what provides a basis for rational behaviour? Ayres et al. (1998) believe that instead of making decisions about acceptable levels of risk, people may seek effective ways of acting. Following Gibson (1979) they proposed that by perceiving affordances[6], people can choose responses without involved conscious thought about possible consequences and the chances. They are broadening the term to also include aspects of more complex situations, e.g. driving safety. Perception of affordances does not require that risk is perceived. If affordances and not risk perception is important, then the likelihood of consequences should be more important than their severity, because affordance is related to whether an action can be done successfully rather than what will happen if it fails. Warning about highly probable consequences of a certain action should therefore be more efficient than warning for an unlikely though more dangerous event. Regarding tunnels, the relatively low probability of dangerous accidents in them could be one of the causes of non-compliance with traffic rules.

[5] There is evidence that the optimism bias is due more to pessimism about others than to optimism about self when risk judgments are compared with objective risks (after Ayres et al., 1998).

[6] Gibson (1979) suggested that we perceive objects or features of our environment in terms of affordances, or the uses to which they can be put. The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill.

Figure 2.4: What was on the mind of a driver trying to turn around his car in a tunnel with one way traffic. This dangerous and prohibited behaviour is caused either by limited awareness of risk or prevailing influence of some other motives. This time due to circumstances and kind behaviour of truck driver everything ended happily. But cameras in tunnels registered a number of dangerous behaviours. (Source: DARS)

On the other hand, perceived affordances of undesired behaviour should be reduced. Publicized and enforced regulations could reduce the perceived likelihood of successful driving (e.g. without penalties). According to Ayres et al. (1998) in some situations it is possible to reduce perceived affordance by demonstrating personal short-term consequences or to focus directly on behavioural change (e.g. by increasing the attractiveness of a desired behaviour with incentives). Simply, *risk communication campaigns are not enough*, though they are much less expensive than other measures. They are good for informing people about hazards, but only in combination with enforcement and other measures they could change drivers' behaviour toward greater safety.

2.3 Tunnels: Accident happening model

In order to understand what is going on in tunnel accidents an *accident happening model* is proposed in Figure 2.5, that is based on integration of Bandura's (1986) model of triadic reciprocal causality, task capability model (Fuller and Santos, 2003), the model of driver behaviour (Rummar, 1991), and recognition-primed decision model (Klein, 1996).

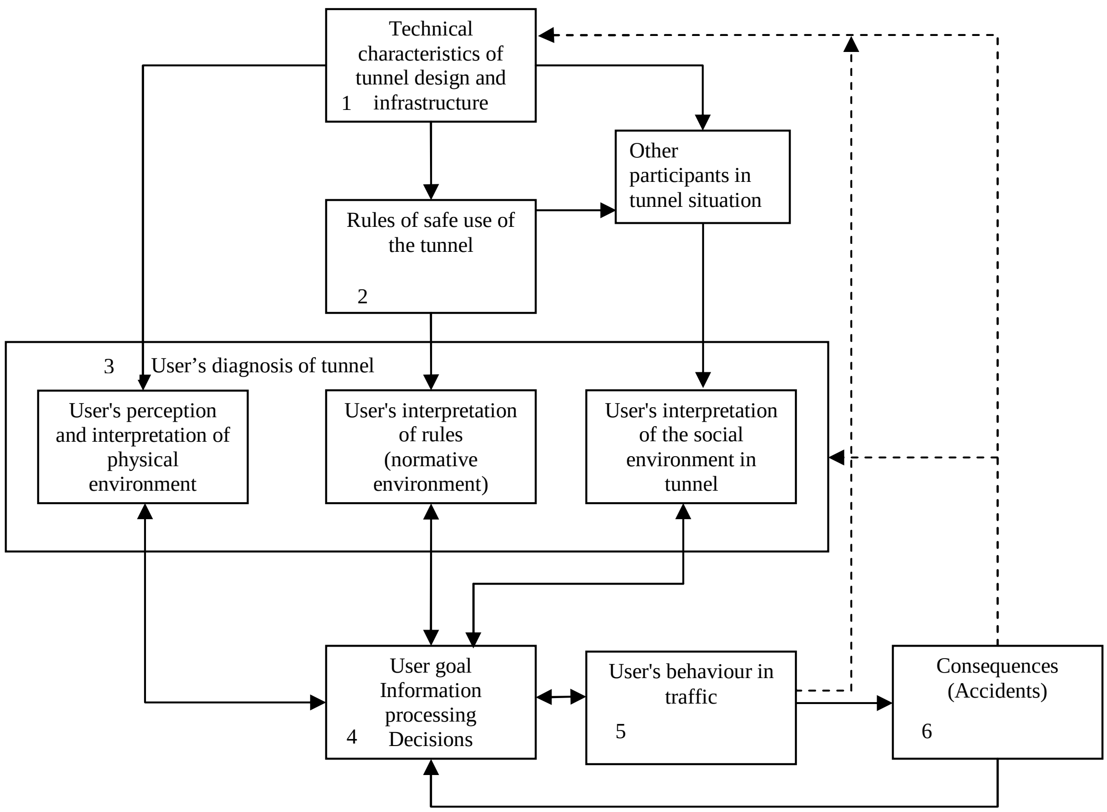


Figure 2.5: Accident happening model is above all a summary of some existing models indicating the complexity of the situation.

Applying this model gives us some key processes that contribute to the safety of tunnel use. The model is focussed on the user behaviour in tunnel; the inputs of the before mentioned stakeholders will be commented at the appropriate place.

Safety considerations in relation to the respective parts of the model:

1. *Technical characteristics of the tunnel design and infrastructure.* Technical solutions of the tunnel such as its design and infrastructure define environmental stimuli. This environment is created by designers on the basis of knowledge relating to various disciplines. In consideration of the proposed solutions the planned role of tunnel users (drivers, operators, and maintenance and emergency personnel) should be taken into account. The available information about the user's behaviour and behavioural consequences should be analyzed for its implications regarding the proposed technical solutions. In the absence of this information the designers proposals are not based on a scientific approach, but on their tacit experiences and knowledge regarding the safe behaviour or on common sense what might results in unexpected consequences.
2. *Rules of the safe use of the tunnel*. Technical solutions in a tunnel imply a set of rules that are important for the behaviour of tunnel operators and users. From the user perspective the rules are

instructions that reduce the possible variability of the user behaviour. Some rules are enforced by tunnel construction, other require users' compliance. The rules are norms that define the "game". Rules define obligatory, permissible and "forbidden" behavioural repertoires. The information about the rules and their violation must be clear to the users and operators. Several processes are relevant for enforcement of rules. First, the utility and necessity of the rule must be considered while designing the tunnel. Second, the process of teaching (transmitting) the rules to users must be provided. Third, the procedures for the control and enforcement of rules must be considered. The tasks of the tunnel operator that relate to surveillance of user's behaviour and tunnel maintenance must be defined in relation to above rules.

3. *Diagnosis of the tunnel situation.* The tunnel infrastructure, the rules of tunnel use, and the behaviour of other participants in the tunnel are the main sources of stimuli that determine user's behaviour. The safety can be enhanced by improving the perceptual characteristics of stimuli (visibility, information saliency) and the appropriate interpretation of the safety situation. Of special importance is the interpretation of the rules, designed for a safe operation. This interpretation is a very complex process that can not be completely controlled. Some errors of interpretation are also due to the time constraints that sometimes do not allow extensive processing of available information. Other circumstances that influence the user's interpretation of the tunnel situation can be subsumed under the label of "traffic safety culture". Safety culture comprise a set of values, assumptions, rules and beliefs about safe driving which traffic participants develop trough their experience in the traffic system.
4. *Behavioural decision making process.* Each tunnel user has a set of goals that s/he tries to achieve in the traffic situation. During driving s/he continually diagnoses the traffic situation, predicts the possible outcomes and decides about corrective actions that fit to the perceived situation. Information processing necessary for this decision making is of two kinds. The first is rational, logical information processing. The task of this processing is to fit the performance with task demands (Fuller and Santos, 2002). This process is more or less conscious and limited to the situation when the processing time is not constrained. Another kind of information processing is automatic. This is especially important in the situations that repeat over and over and where the decision time is limited. Examples of such are Rasmussen's skill-based and rule-based behaviours (Lipshitz, 1995). From the safety perspective the decision based on automatic information processing is of greater importance because the traffic situation is very dynamic one and often there is no time for rational processing. In addition, automatic decisions could be the source of many errors.
5. *User's behaviour in traffic.* The processes of information processing and decision making are not directly observable. We are able to observe only the end result – the driver behaviour. From the safety perspective behaviour considered to be (near) erroneous is of special interest. We can promote safety trough careful registration of drivers' actual behaviour. Accurate and online information of drivers' behaviour is important not only for scientific purposes but also for the work of tunnel designers and operators. Certain behaviour of traffic users requires immediate intervention. For the organization of this intervention the behavioural data about the traffic users are indispensable.
6. *Behavioural consequences.* From the safety perspective the most important consequences are accidents. We must be able to predict risks of all possible kinds of accidents. This is necessary because of the following reasons: improvement of tunnel infrastructure, improvement of system of rules and implementation of rules, and for organization of emergency action to save lives and limit the extent of damages.

The proposed accident happening model integrates the elements of other models in a way that supports the process of designing the road tunnels. The following elements are specifically emphasised:

- The process of designing the tunnel implies the physical, normative and social environment of the tunnel users. In this process existing information about user's behaviour is deployed. The additional necessary information must be obtained with relevant research.
- The process of designing the tunnel is interdisciplinary. The exchange of ideas between different disciplines must be planned.

- The proposed model emphasizes the importance of normative environment (rules for utilization of the tunnel). The rules complement the physical design and are important regulators of the user's behaviour.
- The proposed model emphasizes the fact that the events in the tunnel take place in a social context (other participants). The consequence of this fact is that we must consider the tunnel as a socio-technical system and take into account the processes of so called "*social construction of safety*" (Rochlin, 1999).
- It follows from our model that the process of user's interpretation of the tunnel situation is a major determinant of the safe behaviour. For the understanding if this interpretation, the safety culture of the user must be taken into account. This topic requires more research.
- The model incorporates the difference between automatic and conscious human information processing. Much information relating to safety culture is processed automatically.
- This model emphasises the systemic and circular regulation of the safety in tunnel. One regulatory loop occurs on the behavioural level of the user. The consequences of the user behaviour are feed-back to his interpretation of tunnel situation. The second loop occurs on the system level. The consequences of user behaviour are feed-back to the tunnel designers and operators who make necessary reconstructions and interventions to improve the safety.

2.4 Human behaviour in fires

In their research on fires, Canter, Breaux and Sime (1980) showed that fire is experienced as a complex, rapidly changing event, which, in its early stages at least, is usually highly ambiguous, providing little positive information to act upon. A person confronted with a fire needs a lot of information in order to understand the situation fully and to decide what to do. Canter et al. find characteristic sequences of acts for different fires and propose the general model of sequences (see Figure 2.6).

Especially the points of potential sequence change are important. Three such points appeared:

- The first was immediately after the initial cues at which an 'investigate' or 'ignore sequence can be set in motion;
- The second comes after seeing smoke, at which one of three 'prepare' sequences can be entered;
- The third follows the occurrence of the particular preparation, giving rise to choice between 'wait', 'warn', 'fight' or 'evacuate' sequences.

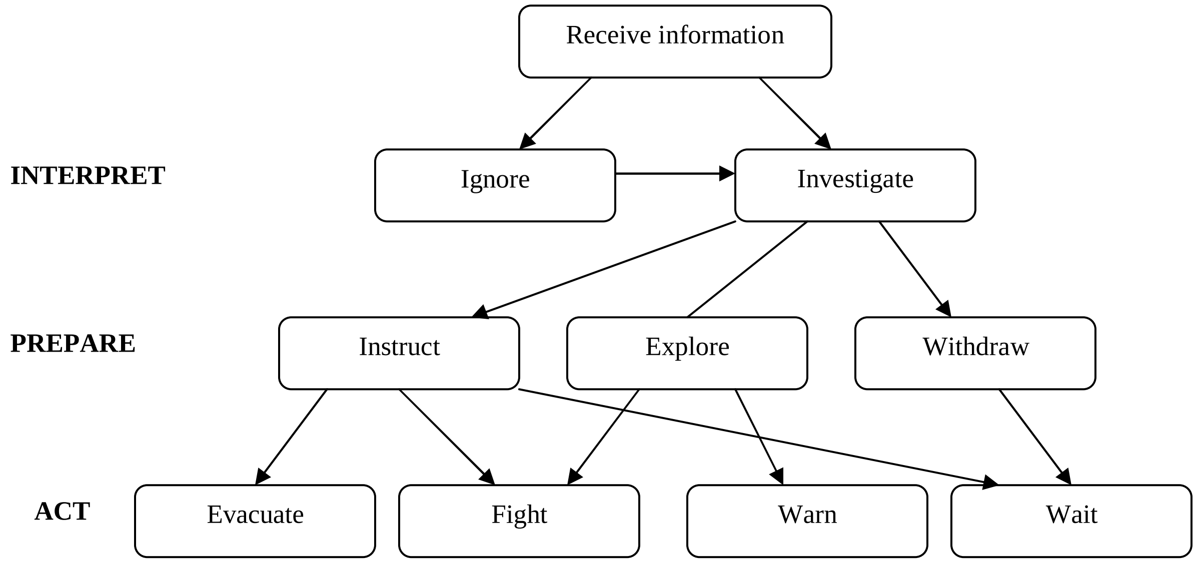


Figure 2.6: Sequences of human behaviour in fires: Summary of the general model (Canter, Breaux and Sime, 1980).

It is evident that potential actions increase in variety as the sequence of behaviour unfolds. This means that while general statements about all fires can be made with some confidence for the initial stages of the sequence, at later stages the actions are more likely to be highly specific to a particular context. Though Canter et al. (1980) did not study fires in tunnels, their findings are applicable also for tunnel situation. For instance, hesitating to take action at the beginning of a fire was shown also in the TNO study on fires in tunnels (Boer, 2002). Boer (2002) from TNO conducted a complex research project about behaviour of drivers on evacuation of a tunnel. Four field studies were undertaken, offering by far perhaps the most concrete findings about what would go on during a tunnel fire. The first study showed that most of the participants (60 %) thought they could evacuate across the roadway (instead of through the emergency exits). Once in the tunnel (Study 2) it was evident that only a quarter of them actually did evacuate across the roadway; the rest took the emergency exit. In the central tube behind the emergency door they were not fully aware of what to do next. Passivity dominated Study 3. The majority of people stayed in the car, even when the first 10 cars were completely obscured by smoke. In only one of the tests spontaneous evacuation occurred, which eventually got bogged down in small discussion groups. Official instructions like "*explosion hazard*" or "*please leave the tunnel*" always brought about an evacuation. Once a few people had gone through the emergency exit door the others followed. The doors were the *bottleneck* of the escape route, however (almost) no real congestion was observed. In Study 4 the effect of sound beacons was studied. Fires in tunnels usually mean the presence of smoke. Given the choice, people will avoid going through smoke, but while escaping fires they frequently have to travel through areas filled with smoke. In tunnels they at least have to find emergency exit doors in smoke.

Figure 2.7: Smoke from the burning cargo could spread very quickly and prevent orientation. In this case the event ended without serious consequences (Source: DARS)

Research (*source*: *internet: www.soundalert.com/way-finding.htm)* into the visibility of exit signs and lighting carried out by looking through a glass window into the smoke filled room or using theatrical smoke, thus ignoring the irritant effect of smoke on the eyes, showed great deterioration of visibility in smoke conditions (Figures 2.8 and 2.10). While it is true that smoke rises when mixed with hot gases, smoke density is not always lowest near the floor. Smoke tends to travel along the ceiling when it mixes with hot, buoyant fire gases. As these gases cool, however, the smoke sinks and eventually fills the entire space. Smoke may also be dispersed evenly through rooms by forced ventilation systems and by the action of sprinklers activated by the fire. Under these conditions low placement of exit signs may offer little advantage.

Figure 2.8: Research carried out by the Building Research Establishment (UK), using volunteers in theatrical (white) smoke illustrates how visibility of different types of exit signs vary in smoke. It ignores the effect of real smoke on the eyes, or toxicity, however it does illustrate that NONE of these technologies is visible at over 1.5 metres in dense smoke (source: internet: www.soundalert.com/way-finding.htm). The use of directional sound is therefore justified.

The use of directional sound to mark exits enables identification of exit locations that are obscured. The sound of a signal should clearly distinguish it from the alarm bells/sirens. Additionally, under non-smoke conditions, the use of The Localizer Directional Sound Evacuation (DSE) beacons draws attention to Emergency exit signs and nearest exits which are often ignored because they are so familiar and not normally important. The Localizer "audible exit sign" enhances fire alarms and lighting systems. Research from the firm Soundalert has stated that The Localizer can reduce evacuation times by as much as 75% in smoke and 35% in perfect visibility (***www.soundalert.com/way-finding.htm***). However, in the study of Boer (2002), most of the people missed the doors because of the smoke with the sound beacons of Sound Alert only being effective with the instruction "*there are sound beacons above the emergency exit doors*". Tunnel users did not associate the sound of Sound Alert a safety indication of where to find the emergency exits. Stated in simple words, the sound itself was not self-explaining enough.

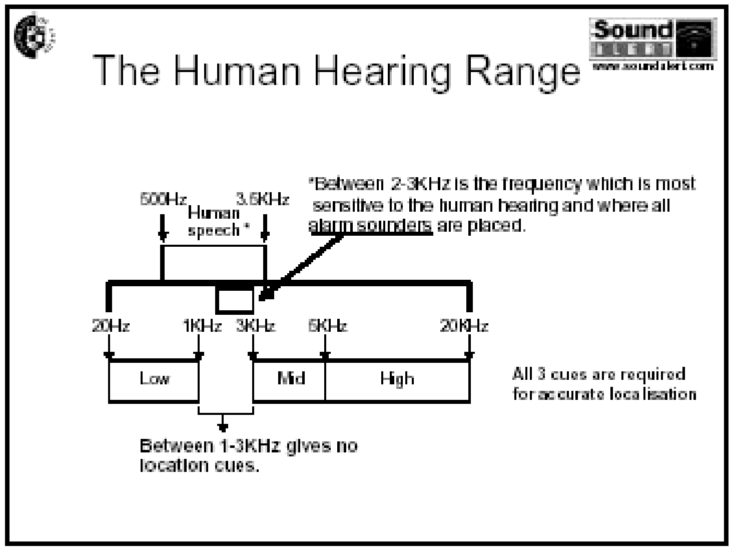


Figure 2.9: Three frequency bands needed for good localization (Withington and Lunch, 2002)

Research using different light sources clearly showed that in smoke light is not enough. Therefore also in tunnels emergency exits should be equipped with sound beacons providing directional information where the exit is. Such equipment may remove the need for having prior experience with the environment, reduce hesitancy and eliminate way finding errors (Withington, 2000). It must be mentioned that a sound to be directional need all three frequency bands, low, mid and high.

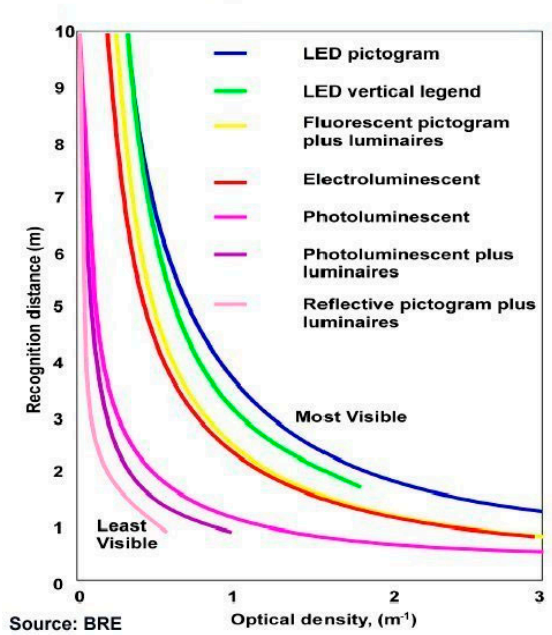


Figure 2.10: Recognition distance at various optical density of smoke. At OD $1m^{-1}$, the best technology was visible at just 4 metres whilst Photo-luminescent signs were visible at just over 1m. (source : internet: www.soundalert.com/way-finding.htm).

We can conclude that without directional sound guidance the confidence of people in their direction of movement will be low and this will affect their speed and the commitment with which they move (after www.dse-web.fsnet.co.uk/human_behaviour.htm). Subjects try to follow whatever clues they can find in smoke conditions. And some of the clues may be wrong. Therefore directional sound can help him. While usual sound alarms only alert people, directional sound is also guiding them.

Withington (1999) is therefore strongly advocating the addition of sound to emergency egress lighting system, giving also theoretical basis for its use. There are three main types of information that allow us to localize sound: loudness/intensity difference between the sound at each ear (IID) and the differences in the time of arrival of the sound between the ears (ITD) (binaural cues) as well as head-related transfer function (HRTF) referring to the effects the external ear (the pinna) has on sound. For single frequencies these cues are spatially ambiguous (cone of confusion). ITD cues are present in sound with frequencies below 1 kHz, IID cues are extracted from sound 3 kHz and above, while HRTF cues work from t kHz and above. The larger the frequency content, the better is the accuracy of sound localization.

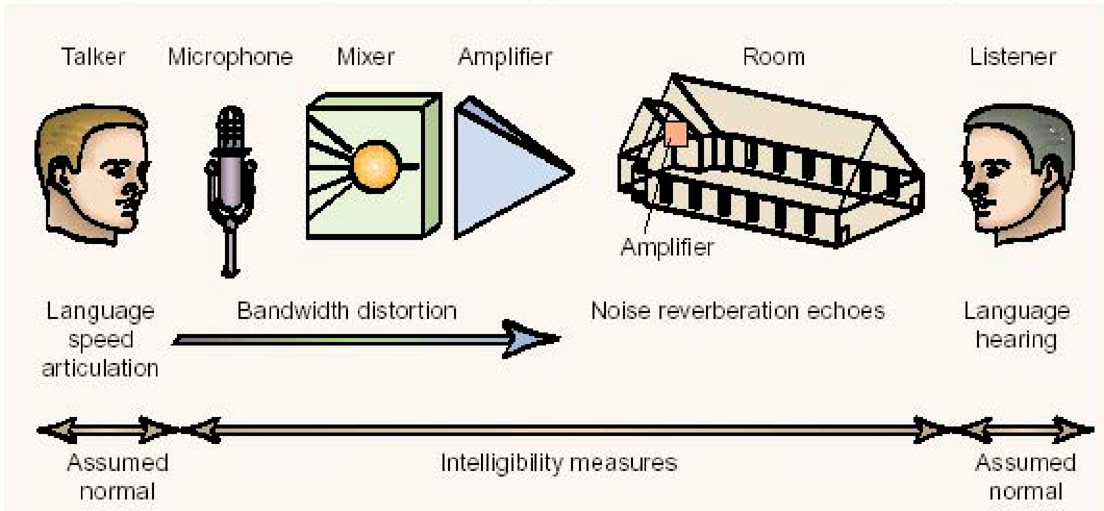


Figure 2.11: Voice Signal Path. The figure shows the types of error that can be introduced into the message at each stage. Problems or faults have a cumulative effect on message understanding (Jacob, 2002, source: www.sfpe.org).

In situations where egress is complex or difficult, human voice is often used to provide *information*. Failure to understand the message content can result in several ways. A message that is not *intelligent* may not be understood. A message spoken in foreign language may not be understood. A person talking rapidly or with a speech impediment can cause a message not to be understood. Even a well spoken, intelligent message in the language native to the listener can be misunderstood if it is not audible or if its delivery to the listener is distorted. Speech intelligibility is the measure of the effectiveness of speech. The measurement is usually expressed as a percentage of a message that is understood correctly. Speech intelligibility does not imply speech *quality*. For speech to be intelligible, it must have adequate *audibility* (sound pressure level) and adequate *clarity*. Clarity can be reduced by: (1) amplitude distortion caused by the electronics/hardware; (2) frequency distortion caused by either the electronics/hardware or the acoustic environment; and (3) time domain distortion due to reflection and reverberation in the acoustic environment. Designers and engineers have the greatest effect on speech intelligibility by their choice of equipment, the number and distribution of loudspeakers, and the power at which they are driven.

But this is only one side of a story. Message should not only be understood, but people must also consider it and comply with instructions. The problem of effective risk communication depends not only on understanding the risks themselves, but also on people's perception and interpretation of the risk. Warnings usually present a very efficient measure in prevention or mitigation of the serious consequences of disaster, under condition of course, that they are timely, and adequately formed and presented. Quarantelli (1984) believes that a warning is far more than a linear transmission of a message from a warning source to the public. Above all, the message should be clear, concrete, perceived as relevant and should *direct* people what to do. As the response to the warning involve a *definition* of the situation, the warning must caused a shift in perception of safety, from being safe to being unsafe and direct the action of threatened people. First reaction to warning is usually *denial*, as people are prone to normalcy. Alarms are more likely to indicate to people that something is wrong, than to mobilize them to a direct response. Warning delivered by governmental officials or emergency organization personnel are more likely to be believed than if delivered by private citizens. Lindell and Perry (1987) ascertained that it follows from the disaster literature that three steps intervene between the receipt of warning message and the adaptive response, namely: *milling* (message confirmation and information gathering), *assessment of personal risk* (proximity, certainty and severity of impact) and *assessment of the logistics of response* (protection possible, plan available and family together). We should consider them also in this case. During the accident in tunnel, people will observe what other road users or personnel are doing and this could be a stronger clue for activity than the warning itself.

This idea of directional sounds to evacuate tunnel users was further assessed in an extra study performed in a co-operation between RWS and TNO. In this, several sound messages were evaluated. The outcomes of this study was also used as input for the innovative evacuation system for low visibility conditions.

Based on the literature described in UPTUN Deliverable 3.2 and the literature described in Chapter 1 (Introduction), we can state that there is still a lack of knowledge about how to improve tunnel safety from the human perspective. The remaining part of the report will focus on studies that were done in order to develop more knowledge about these topics. With the results of these studies, recommendations will be done on how to improve human behaviour in cases of emergencies in tunnels.

If we summarize, the following general objectives should be considered in ensuring tunnel safety:

- ⇒ Construction of tunnels which takes into account also the needs and characteristics of tunnel users (e.g. perception, boredom, information needs, etc.);
- ⇒ Adequate management of tunnels (e.g. controlling entrance into tunnels especially dangerous cargo, surveillance of situation and prompt reactions to deviations, speed control, etc.);
- ⇒ Informing, educating, training and enforcing tunnel users for safe behaviour in tunnels (e.g. inclusion of the content about safe behaviour in tunnels into training courses, safety campaigns, leaflets with information about safe behaviour and behaviour in the case of danger,
- ⇒ Training of managers and tunnel staff for adequate behaviour in the case of accident including exercises;
- ⇒ Regular following of the safety situation and give effect to the newest safety measures;
- ⇒ Exchange of experiences and harmonization of the situation in EU countries.

3. DRIVING SIMULATOR STUDIES

G. Jenssen, M. Terje & Cato Alexander Bjorkli
Sintef, Norway

M. Martens
TNO, the Netherlands

In the past, some initiatives were taken to focus specifically on the tunnel user. The PIARC C5 Work Program started the Working Group 3 Human Factors of road tunnel safety. This committee expressed the need to give guidance to users to evacuate from the affected tunnel tube as early as possible on their own, but that the real problem is the lack of understanding what is going on. This committee felt that the initial stage of a fire in a tunnel is most critical. Measures aimed at achieving the highest possible level of safety in road tunnels should also focus on alerting and educating road users, leaving no room for wasting time. Among other things, this idea resulted in a leaflet 'Safe driving in tunnels', provided by the European Commission (see Appendix 1). This leaflet is supposed to provide road users with information about the equipment available in tunnels and how they should behave in case of normal situations, traffic queues, accidents and fires.

However, before actually deciding what type of information should be provided, we still know too little about the way people deal with these situations. When do people start to realise that something is really going on? Do they actually understand the danger involved? Maybe there is a specific reason they stay inside their cars? The only things we can learn from real accidents is the mistakes that we feel people made, but we do not have any idea what they thought, how they interpreted the information and why they made the decisions that became fatal. This was an area that we felt was greatly unexplored. And a second question was, if we know how people reason, can people actually apply this information in case they get into these accidents. For example, the EU leaflet makes the distinction between how to behave in a traffic queue and how to behave in case you are in a tunnel with another car on fire, but are these situations really that different? Could it not be the case that people think they are in a traffic queue, but they are actually in a queue behind a vehicle that is on fire? When do people realise there is something more going on, and what are they thinking when they see smoke, are they aware of tunnel evacuation doors?

In order to get a better understanding of the cognitive reasoning during such incidents, TNO Human Factors (the Netherlands) and SINTEF (Norway) each conducted a driving simulator study. In this, the reasoning process of driving in an accident is followed by means of verbal protocols while driving and being in the tunnel. In this study, the effects of having read the EU leaflet and the help of the tunnel operator are being assessed.

TNO Human Factors conducted a driving simulator study with a normal passenger car and SINTEF conducted a driving simulator study with professional truck drivers. First, the TNO driving simulator study will be described and secondly the SINTEF driving simulator study. Because of the readability of the deliverable, not all details were included in this deliverable. For more details, a request of the papers can be sent to either TNO or SINTEF.

3.1 Passenger Car Driving Simulation

3.1.1 Method

Apparatus

During experiments, the subject was seated in a fixed base mock-up of a BMW 318 (see Figure 3.2) and had all normal controls (steering wheel, accelerator, brake, car had automatic gear shift) at his disposal. Based on these control signals, a mathematical vehicle model computed the momentaneous state of the vehicle model.. Feedback of steering forces and gas pedal forces is given to the driver by means of electrical torque engines, and of sound by a sound generator system.

The Supervisor plays a central role in the driving simulator.

- It controls the experimental scenario; as a part of that, it controls the presence and behaviour of other traffic
- It receives data from the vehicle model PC and passes information on to various other sub-systems.
- It carries out the storage of data.

The momentaneous position and heading angle of the vehicle are transmitted via a supervisor computer to a SimFUSION Computer Generated Imaging (CGI) system, which computes the visual scene as seen from the position of the driver. This image is projected on a screen in front of the mock-up.

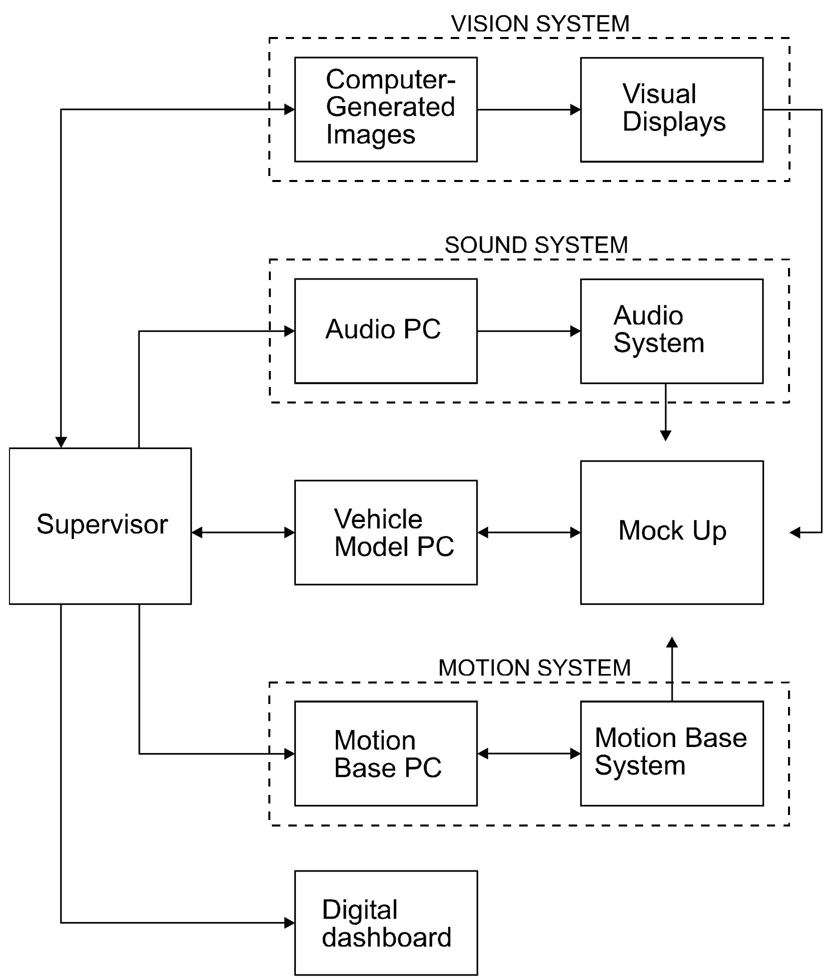


Figure 3.1: Block diagram of the TNO driving simulator.

The generation of the visual images by the CGI takes some calculation time of about 66 msec. This yields a pure time delay in the simulated vehicle system that is not present in the real vehicle. A predictive algorithm has been added to the Vehicle Model (Hogema, 1992; Hogema, 1993) to compensate for this delay. Thus, the output of the Vehicle Model consists of both the actual position and the CGI delay-compensated position.

The Sound System generates real-time sounds in the Mock Up of the driving simulator and provides the subject with sounds of the engine, tyres, driving wind and nearby other vehicles. The Sound System generates '3D-audio'. The direction from which the subject in the mock up hears each sound component matches the location of the sound source in the simulated environment. For example, when a subject overtakes a truck, the sound of that truck will first appear to come from ahead, then gradually move to the right, and finally from behind the mock-up.

The *Motion Base PC* receives input from the Vehicle Model PC by means of an Ethernet communication link. The Motion Base PC transfers its input signals to commands for the Motion Base System. The *Motion Base System* is a 6 Degrees Of Freedom (MOOG 2000 E) hexapod motion platform with the associated control equipment. Only the mock-up is placed on the platform; the RGB projectors and the projection screen are stationary.

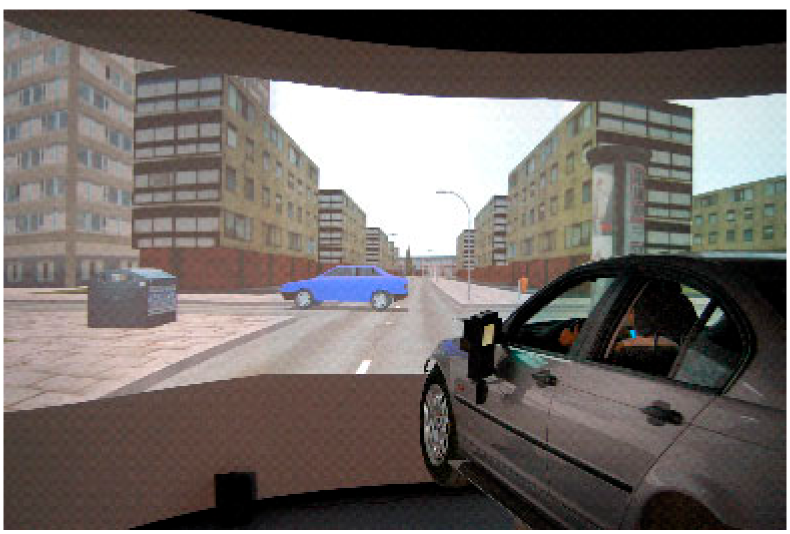


Figure 3.2: BMW mock-up in the TNO Driving Simulator.

Subjects

In total, 60 subjects participated in the TNO driving simulator experiment, randomly assigned to one of 3 conditions. Data of 2 subjects had to be deleted because of disrupted data, leading to 18 subjects in condition 3. The three experimental conditions were:

Condition	
1	People encountered an accident in a tunnel and were not provided with any extra information (control condition)
2	People encountered an accident in a tunnel and had read the EU leaflet about 'safe driving in tunnels' before starting the experiment
3	People encountered an accident in a tunnel, had read the EU leaflet beforehand and received two specific instructural messages while inside the tunnel from a virtual tunnel operator (voice message).

This resulted in a final group of 58 participants. In condition 1, 20 subjects participated (14 male, 6 female) with an average age of 44.1 year (range equals 22-65) and an average driving experience 22.8 years (range equals 4-40) with an average of 23,000 kilometers per year (range equals 1,500-48,000). Condition 2 consisted of 20 participants (11 male, 9 female) with an average age of 45.4 years (range equals 20-65) and an average driving experience of 24.2 years (range equals 2-42) with an average of 22,000 kilometers per year (range equals 2,500-100,000). Condition 3 consisted of 18 participants (8 males, 10 females) with an average age of 39.2 years (range equals 20-65) and an average driving experience of 18.4 years (range equals 1-45) with an average of 13,000 kilometers per year (range equals 2,000-30,000). All subjects were paid for their contribution, but were recruited on a voluntary basis.

<u>Scenarios</u>

Subjects completed 4 rides in the TNO driving simulator. The TNO driving simulator is a ‘high-end’ simulator with the following subcompnents:

All rides were on a motorway, including a 2 km long tunnel. The motorway was a 2-lane motorway, with also 2 lanes inside the tunnel (one-way traffic). There was no emergency lane available inside the tunnel, only a lane of about 1.10m width (as was also the case on the left side). The tunnel had emergency escape doors inside as well as first aid posts with fire extinguishers (clearly marked as such).

The first 3 drives were only to get used to driving in general and to driving in the simulator in particular and therefore nothing peculiar occurred. Other traffic was surrounding the subjects (on both lanes).

Subjects were asked to perform a verbal protocol during all the rides, meaning that they had to speak out loud and name everything that they saw, that drew their attention, that they looked at, that they were doing or that they were thinking. This way we wanted to get a better understanding of what they noticed, when they would take certain actions and why. No examples of a verbal protocol were given to the participants, since we did not want to give any directions as to how they should perform this task. When participants did not verbalize their thoughts very much during any of the first 3 rides they were encouraged to do so explicitly by the experimentor.

The verbal protocol was taken as the main dependent measure. Behaviour was also measured, but it might not be absolutely valid; it could be the case that subjects would not actually leave the vehicle because they were in a simulator. In this case, speaking out loud that they would now leave the vehicle was sufficient.

In ride 4, just before entering the tunnel, the traffic intensity would increase, leading the cars around the participant to slowly brake. This slowing down of traffic is the result of a simulated accident with two vehicles. This accident happens 1 kilometer downstream of the subject. The traffic signaling above the driving lanes is activated (first indicates 70 km/h and the next sign indicating 50 km/h, as is generally the case in the Netherlands to warn for an upcoming traffic queue). In the tunnel the other traffic eventually comes to a complete stop inside the tunnel. After coming to a complete stop, the traffic hardly moved anymore. Three and a half minutes after the virtual accident happened, smoke appears in the tunnel coming from the front towards the participant in the car, getting thicker and thicker. The experimenter observed the participants from the control room. The simulation was stopped shortly after a participant indicated that he or she would now leave the vehicle or when they actually got out of the car. If a participant showed no response (either verbal or nonverbal) indicating they would leave the vehicle, the experimentor waited about 10 minutes before he stopped the simulation.

As was already mentioned, the three conditions differed from each other in the amount of information that was provided to the participants before the start of the experiment and during the experiment. In Condition 1, participants were given no information on how to handle an incident in a tunnel on forehand or during the experiment. They were just told that they would participate in a driving experiment and that they were supposed to drive as they would normally drive and perform a verbal protocol (see Appendix 2). In condition 2 and 3 all participants received the same instruction as in condition 1, but also read the leaflet issued by the European commission about best behaviour in tunnels before they started the experiment. In Condition 3, besides reading the EU-leaflet, participants also received information from a virtual tunnel operator during the experiment: 1 minute before the smoke would appear (and 2.5 minutes after the virtual accident), the operator would say (a standardised voice-recording): "Please turn off the engine. I repeat, please turn off the engine" (this was indicated in the EU leaflet as best behaviour). One and a half minute after the first operator message (30 seconds after the smoke had appeared) the operator voice would say: “Please go to the escape exits, I repeat, go to the escape exits“. (this was also indicated in the EU leaflet as best behaviour). The idea was to provide the standard Dutch messages that would normally be given under those circumstances. However, after discussions with Dutch tunnel operators, we found out there is no such standard message. Therefore we provided subjects with a message made up by TNO.

<u>Procedure</u>

After arrival at TNO, participants received written instructions (as indicated in Appendix 2) and depending on the experimental condition they were assigned to, they were given the EU leaflet to read first before starting the simulator experiment (Condition 2 and 3) as indicated in Appendix 1. After completing ride 4, participants were asked to fill out a questionnaire (see Appendix 3). Participants that indicated to have problems with nausea or motion sickness were allowed to stop the experiment immediately.

After data collection, all data were analyzed. For each participant it was determined what type of reasoning took part and what type- if any - action took place when confronted with a traffic jam and still standing traffic inside a tunnel, followed by smoke in the tunnel. The order in which these actions occurred was also assessed as well as the time it took them to initiate an action after coming to a complete stop in the tunnel. Also, we recorded the time to action after the first moment the smoke could be observed by the participants. It was also noted when participants mentioned they planned to use the emergency exits, when they mentioned the leaflet as a source of information on what to did, or when they exclaimed they did not know what to do. Differences between conditions were determined using statistical descriptions and analyses.

3.1.2 Results

Objective data

In this category of results we looked into what people actually did or how they behaved under the circumstances. In this, we basically looked at what point in time they performed specific behaviour (switching off the engine, putting on the radio, take off the seat belt, and get out of the car). We mainly concentrated on the behaviour that was suggested in the EU leaflet, with an extra category of taking off the seat belt. Since some people indicated in the questionnaires that they did not really go out of the car since it was a simulated situation, taking off the seat belt might have been an indication of the preparedness to get out. The category 'leave vehicle' is based on a combination of objective data (people actually leaving their vehicle) and verbal data (derived from the verbal protocols), since more people tended to verbally indicate that they would leave the vehicle rather than actually do it. If the combination with the verbal protocols would hereby not be made, the conclusion might be falsely drawn that no-one intended to get out of the vehicle.

Table 3-1: Percentage of participants who took action per condition after coming to a complete stop in the tunnel.

Condition	engine off	radio on	safety-belt off	leave vehicle (verbal)
1	60%	25%	35%	65%
2	70%	35%	70%	75%
3	100%	33%	89%	94%

What we see in Table 3-1 is a large difference between the conditions and categories. When we look at the action 'switching off the engine' we see that about 60% of the drivers take this action spontaneously (condition 1, no information). This number only increases to 70% if participants have read the leaflet before the start of the experiment, where this action was specifically mentioned as required. Only with the help of the operator (in condition 3 the operator asks you to do this), this percentages receives the required 100%.

When we look at the second action, that is switching on the radio to search for specific messages concerning a possible accident, this is still a very low percentage for all conditions (25-35%). Only 25% of the road users takes this action spontaneously, but reading the leaflet only slightly increases this percentage (even though the leaflet speaks about turning on the radio to listen to messages). In this case, the leaflet is not specifically helpful in raising the awareness of the importance of using the radio as a form of acquiring information. When we use the behavioural category 'safety-belt off' we see that about 35% in condition 1 take the seat belt off, with an increase to 70% for the people who read the leaflet and 89% to those people who get additional information from the tunnel operator. If we see this behaviour as a preparedness to get out of the car, we see that there is extra preparedness to leave the vehicle when people read the leaflet, and even more so if the operator tells them to go to the emergency exits. This is confirmed by the combination of verbal and behavioural data about leaving the vehicle: from 65% who spontaneously leave or mention wanting to leave the vehicle without any specific information, this increases to 75% for those who read the EU leaflet to even 94% if the tunnel operator provides additional information. However, even with reading the leaflet and an operator telling them to go to the emergency exits, the percentage does not reach 100%.

Besides measuring how many people took action, it is also important to know how much time passes before they actually get to this action. The time was measured between coming to a complete stop and taking action (ofcourse only for those who did take action).

Table 3-2: Time passed in minutes and seconds (per condition) after coming to a complete stop in the tunnel until action

Condition	engine off	radio on	safety-belt off	leave vehicle (verbal)
1	3.17	2.13	3.23	3.16
2	1.27	1.35	2.45	2.54
3	1.06	1.12	2.25	2.23

What we can learn from Table 3-2 is that for condition 1, it took on average 3 minutes and 17 seconds after coming to a complete stop before switching off the engine. Since there is smoke coming in the tunnel after 1.5 minute, it takes them 1 minute and 47 seconds after the smoke appeared that they switched off the engine. This means that a lot if time is being wasted with the cars putting exhaust gases into the tunnel. However, in condition 2, the engine was on average being switched off before the smoke appeared, probably due to reading the folder. In condition 3, it took on average 1 minute and 6 seconds after coming to a complete stop before they switched off the engine. Since there was an announcement to switch off the engine 1 minute after coming to a complete stop (so 30 seconds before the appearance of the smoke), this means that almost immediately after the announcement they switched off the engine.

What we can learn from this is that for all actions, the combined leaflet and operator lead to the shortest response times. So even though the tunnel operator only provides information about the engine off and getting out, also response in other actions result in the shortest times. For switching off the engine, the time difference between reading the leaflet and reading the leaflet and an operator message was very small. But note that more people actually did switch off their engine in condition 3 (after 1 minute, the announcement was made). Table 3.2 shows the average time, although the longest time is also interesting. For leaving the vehicle (verbal indication) this varied from 2 minutes and 25 seconds after coming to a complete stop to 7 minutes and 8 seconds for the first condition (for only those 65% that actually indicated to leave). For condition 2 this varied from 2 minutes and 22 seconds to 4 minutes and 9 seconds (for the 75% that actually indicated to leave). For condition 3, this varied between 1 minute and 51 seconds and 3 minutes and 7 seconds for the 94% that verbally indicated to leave their vehicle.

It is also interesting to see how much action was actually the result of the appearance of the smoke. Table 3-3 shows the percentage of people who took action only after the smoke became visible. In brackets, the percentage of people is indicated who already took action before the appearance of the smoke.

Table 3-3: number of participants who took action per condition after smoke occurred (between parentheses the number of people who had already turned off engines etc.)

Condition	engine off	radio on	safety-belt off	leave vehicle (verbal)
1	55% (5%)	5% (25%)	35% (0%)	65% (0%)
2	20%(50%)	10% (30%)	60% (10%)	75% (0%)
3	0% (100%)	33% (0%)	83% (6%)	94% (0%)

This information is most interesting is we also know how quickly after the appearance of the smoke people came to action. Table 3-4 shows these response times. On average, only 1minute and 20 seconds after the appearance of the smoke, people actually turned off the engine in condition. This was only after they verbally indicated to leave the vehicle and after they already took their safety-belt off. Here it would be easy to conclude they only switched off the engine since they wanted to leave their vehicle. The times of indicating to leave the vehicle for condition 1 varied from 11 seconds to 5 minutes after the appearance of the smoke (for the 65% that actually indicated to leave the vehicle). For condition 2, the engine was switched off on average just 16 seconds after the smoke became visible (by 20% of the drivers, 50% already switched it off before, see Table 3-3). Only seconds after that, they indicated to leave their vehicle and took their safety-belt off. The times when indicating to leave their vehicle after the smoke became visually present varied from 15 seconds to 2 minutes for condition 2 (for the 75% that actually indicated to leave). In condition 3, people put on the radio only 20 seconds after the appearance of the smoke, and hardly wasted any time after this too speak out loud they would leave the vehicle and unfasten their safety-belt. The times of indicating to leave the vehicle varied for this condition from 4 seconds to 45 seconds after the appearance of the smoke.

Table 3-4: time passed in minutes and seconds (per condition) after smoke occurred in the tunnel until action

Condition	engine off	radio on	safety-belt off	leave vehicle (verbal)
1	1.20	3.14	1.13	1.06
2	0.16	1.04	0.42	0.4
3	0	0.2	0.32	0.26

For condition 3, it is not fair to say that everyone already switched off the engines by themselves: they were told to do so even before the smoke appeared. An average of 10 seconds passed after announcement 1 before participants turned off their engines. One participant, however, had already switched off the engine before the announcement was made.

Nine participants had already indicated that they would leave the vehicle before announcement two was made. One participant did not follow-up on the announcement and indicated that he was not going to leave the vehicle. The remaining eight participants took an average of one minute and 23 seconds after the second announcement was made to indicate that they wanted to leave the vehicle. Obviously these data (time to action after announcement) were only acquired in Condition 3.

Verbal transcripts results

As was stated before, subjects were requested to speak out loud continuously. By doing that we hoped to get more information about the way people came to decisions. Since it will go too far to include all remarks, a summary of the most important remarks is summarised in Appendix 4. The most important issues from these remarks will be discussed in this chapter.

In condition 1, in which people did not get any extra information, all subjects were occupied with the traffic queue at first, in which all subjects interpreted this as peak hour traffic, and not yet s an incident.

Some things are especially worth mentioning:
Besides all participants who did not mention specifically how they would escape, some people specifically mentioned that they planned to walk back to the entrance of the tunnel. In Condition 1, five participants mentioned to do this; in Condition 2 one participant mentioned this and in Condition 3 none. This is interesting since the idea is that all tunnel users use the emergency evacuation doors to escape. Since all subjects already drove the tunnel 3 times before and had a chance to see the exits inside the tunnel on ride 4 as well, apparently some people still want to use the tunnel entry as an exit. In the last group, in which it is specifically mentioned by the operator, no-one mentioned this.

On the other hand, of those who did tell how to escape and were not planning to use the tunnel entrance, one participant in Condition 1 specifically mentioned planning to use the emergency exits, four participants in Condition 2 planned to do so, and three in Condition 3. These results together suggest that the EU leaflet had at least some positive effect on the awareness of the emergency exits, and the operator may have had a slight positive effect on this as well. Even though some people might have gone for the emergency exits, they did mention this specifically, which makes a proper indication of the leaflet and the operator impossible.

Not surprisingly no-one in Condition 1 mentioned the EU leaflet, two participants in Condition 2 spontaneously mentioned the leaflet and one participant in Condition 3 mentioned the EU leaflet as a source of information. Some people specifically mentioned that they knew they had to use the radio for specific messages, but that they forgot what frequency (a specific frequency is mentioned in the leaflet).

In Condition 1 6 out of 20 participants mentioned they had no idea what to do in the given situation, in Condition 2, four participants out of 20 mentioned they did not know what to do, in Condition 3, two out of the 18 participants did so. Even though specific information is provided and on condition 3 an operator is present, not everyone is so certain on how to behave.

Questionnaire

In this section the results of the questionnaire will be presented per question. For each question the type of answer categories will be given as well as the percentage of participants per condition that gave the answer falling in this category.

Question 1: Describe in short what happened according to you in the last drive.

Table 3-5: Answers on question 1 in percentages of participants per Condition and in total

Condition	fire in car	fire in tunnel	smoke	accident	motor problems	explosion	traffic jam
1	55%	10%	20%	5%	5%	0%	5%
2	20%	30%	15%	5%	5%	15%	11%
3	28%	33%	17%	0%	11%	11%	0%
Total	35%	24%	17%	3%	7%	9%	5%

The answers to question 1 fall into seven categories. The first category: “fire in car”, includes only answers that include the remark that there was a fire in a car. The second category includes answers where the participants concluded there was a fire in the tunnel without referring to a car being on fire, but merely fire in general. The third category consists of answers that only include references to smoke, but not that the smoke was the result of a fire. The fourth category: “accident”, consists of answers that referred to the occurrence of an accident and no mention of a fire, smoke or an explosion. The category: ”motor problems” refers only to answers that include a reference to a boiling motor of a car as the source of the occurring smoke. Only two of the four answers included a reference to smoke. However these participants specifically mentioned that the smoke was white and thus had to originate from a boiling motor. The other two participants did not mention the smoke at all, only motor problems. Interestingly, both these participants did not react adequately. They did not turn off their engine, or leave their vehicle (see also later in this report). The category: ”explosion” consists of answers that refer to an explosion as the source of the occurring smoke. All answers in this category included a reference to smoke.

In summary, the majority of participants thought that there was a fire, a total of 65% for condition 1, 50% for condition 2 (with leaflet) and 61% in condition 3 (leaflet and operator). In fact most people registered something was wrong and most participants concluded some sort of accident must have occurred. Only 5% of all the participants (1 person in condition 1 and 2 in condition 2) were not sure what had happened (answer in the category “traffic jam”). Although all three mentioned the traffic jam they encountered they did not give an explanation as to why the traffic jam occurred in answering question 1 of the questionnaire. Interestingly so, these participants did react adequately: all three turned off their engines and mentioned they would leave the car in the verbal protocols. This is confirmed in the next questions of the questionnaire where these same three participants do give an adequate description of the situation. In answering these questions, there does not seem to be a large help from either reading the leaflet or from the operator. This may be explained by the fact that the leaflet and the operator provide more help on how to behave than on understanding the situation in such.

Question 2: When did it occur to you what was going on?

Table 3-6: Answers on question 2 in percentages of participants per Condition and in total

Condition	saw smoke	smoke intensified/ closer	traffic jam and smoke	total smoke	traffic jam	other	total traffic jam
1	35%	35%	20%	90%	10%	0%	30%
2	40%	15%	30%	85%	5%	10%	35%
3	50%	11%	11%	72%	17%	11%	28%
Total	41%	21%	21%	83%	10%	7%	31%

The answers to question 2 fall into five categories. The first category 'saw smoke' only includes answers in the line of: "When I saw the smoke it occurred to me what was going on." The second category includes answers in the line of: "When I saw the smoke intensify or coming closer it occurred to me what was going on." The third category includes all answers of participants that first mention the traffic jam and then the smoke as a reason for them to understand what was going on. These three categories can be combined in one category 'total smoke' (in italics), since all these participants mentioned the smoke as a trigger to understand what was going on. Almost all participants (over all categories an average of 83%) mentioned the smoke as an indicator for them to understand what had happened in the tunnel. The fact that the smoke intensified or that it occurred in combination with a traffic jam was important for almost half of that group to determine what was going on. One can also combine the two categories that include mentioning the traffic jam. Since the traffic jam occurred earlier in time than the appearance of the smoke one can say that participants mentioning the traffic jam as a reason to understand what was going on were sooner concerned or alarmed than the participants merely mentioning the smoke. No major differences between Conditions could be observed. In the category "other" four different answers were included. For Condition 2: "at moment of explosion and lights" and "almost immedeatly, turned on emergency lights and would have normally ran away". For Condition 3:"When it was announced to go to the emergency/flight doors", "I was alert, but when it was announced that the engine should be turned off I realized how severe the situation was".

Question 3: What kind of information did you use to understand what was going on?

Table 3-7: Answers on question 3 in percentages of participants per Condition and in total

Condition	visual				announce-ment	traffic jam	radio	intuition	other
	lookin g	saw smoke	what others do	total visual					
1	5%	10%	20%	35%	0%	15%	15%	10%	15%
2	15%	5%	25%	45%	0%	20%	15%	5%	20%
3	0%	6%	17%	23%	56%	11%	6%	0%	11%
Total	7%	7%	21%	35%	17%	16%	12%	5%	16%

The answers to question 3 fall into six main categories. The first category is labeled 'visual' and consists of three subcategories. This means that the main source of information that participants mention is visual information, but what type of information they used differs. The first sub- category 'looking' consists of answers that include a reference to looking or seeing, but no explanation of what they saw. In subcategory two 'saw smoke' participants mentioned they looked for information (visual search) and saw smoke. This was the information they used to understand what was going on. In subcategory three 'what others do' participants mentioned they were also looking around to find information, but instead of the smoke, they looked at what other people were doing as a source of information to understand what was going on (note that in this experiment, the other drivers did not do anything but stop). A total of 35% percent of the participants used visual information to understand what was going on, but within that group, people were looking for different things. Compared to condition 3 there were more people in condition 1 and 2 that mentioned visual information as a source of information to understand what was going on. This is explained by the fact that in condition 3, participants mainly mentioned the announcement of the tunnel operator (category ”announcement”) as their main source of information to understand what was going on (56% of the 18 participants in Condition 3). Other sources of information were the fact that there was a traffic jam (category 'traffic jam'), the radio or intuition (categories 'radio' and 'intuition'). The last category 'other' consists of a number of different sources of information, such as: ‘experience with cars’, ‘tried to stay calm’, ‘the smoke’, and ‘tried to find the knobs to regulate the heat’.

Question 4: When did you decide to take action or, what refrained you from taking action (no action)?

Table 3-8: Answers on question 4 in percentages of participants per Condition and in total

Condition	smoke		Information from different sources		simulation	other people	sensation	other
	action	no action	action	no action	no action			action
1	50%	0%	0%	6%	15%	15%	5%	10%
2	55%	10%	0%	15%	10%	0%	0%	10%
3	56%	0%	28%	0%	11%	0%	6%	0%
Total	53%	3%	9%	7%	12%	5%	3%	7%

The answers to question 4 fall into six main categories. Each category is divided into two subcategories describing whether the result of the decision was action or no action.
The first category 'smoke' includes answers that range from: "when I saw the smoke" to "when I saw the smoke coming closer" or "when the smoke thickened". Two participants in Condition 2 did not take action because of the smoke. One person said the smoke was too thick to approach the accident. The other person said the smoke was not very thick and that he therefore did not see any reason to go out of the car. The category 'information from different sources' includes answers in two different subcategories. The subcategory where the participants mentioned that they did take action all referred to the announcement over the loudspeaker (these answers occur in condition 3, the only condition in which the operator announced something by means of loudspeakers). In the subcategory where the participants mentioned that they did not take action the answers included general uncertainty, missing information from signs or radio, or a definite cue. One person in Condition 2 said he/she decided to wait for some signal in the tunnel to leave the car. Another person in that same condition (2) said to miss information from signs and radio. One person in condition 3 said it was unclear where to go to, otherwise he/she would have stepped out of the car, the second person in that condition (3) said it was unclear overall and he/she waited for more clarity. The third category 'simulation' included only answers of participants who in the end claimed not to have taken any action because of the simulated situation. Some (6) participants mentioned that in real life they would have taken action. One person in the category “simulation” of condition 2 said not to know whether to step out of the car and one person in the category “simulation” of Condition 3 mentioned the fact that this was not a real car and the people were not real as a reason not to take action.

Both the fourth and the fifth category only include, as did category 3, answers of participants who in the end did not take action. The category: 'other people' includes the answers of three people, all in condition one, who were waiting for other people to take action so that they could follow. Interestingly, this category is 0% for both condition 2 (leaflet) and condition 3 (leaflet and operator). The fifth category 'sensation' includes two answers. One person (condition 1) said that he felt safer in the car and therefore stayed, the other person (condition 3) said that he actually wanted to get out of the car earlier but was afraid (without stating why). The category 'other' included answers of people who took action and only two stated what they did without giving a reason why they did so. One person (condition 1) said he would walk back to the end of the tunnel because the cars where standing still, and another person in condition 1 said that he went into the middle lane to see what was going on. In condition 2, one person stated that he/she closed the windows immediately and turned off the engine and one person said he took immediate action, without saying what that action was.

In general the answers to question 4 reflect the answers to question 3. Participants in Condition 3 did not only see the announcement of the tunnel operator as a way to understand what was going on but also sometimes a reason for taking action. Participants in Condition 1 and 2 mentioned they missed information and therefore did not take action. Seeing the smoke however, is still the major clue as to what to do (more than 50% takes action after seeing the smoke). An almost even number of people in every Condition said they did not take action because the situation was not real but simulated with an average of 12% over all conditions.

Question 5: Why did you do what you did?

Table 3-9: Answers on question 5 in percentages of participants per Condition and in total

Condition	smoke/fire	to survive	not necessary	announcement
1	25%	25%	25%	0%
2	25%	30%	30%	0%
3	28%	11%	6%	40%
Total	26%	22%	21%	12%

The answers to question 5 fall into four categories. In the first category 'smoke/fire' participants mentioned that they were afraid of the smoke or they could not see because of the smoke or thought smoke to be unhealthy. One person (in condition 3) also mentioned that reading the folder was a trigger to know what to do.

The second category 'to survive' includes answers that all relate to the will to survive as a reason for doing what they did. The third category 'not necessary' includes answers of participants who did not see the necessity to do anything at all because they did not want to panic, did not see enough panic, felt it was safer in the car, looked for more information and, tried to stay calm. Here, reading the folder (condition 2) did not result in less people in the category 'not necessary'. Only on condition 3, reading the leaflet and having an operator statement lead to less people stating action was not necessary. There was still one person in Condition 3 who did not see any reason for action (even though the operator tells people to leave their vehicle) compared to five people in Condition 1 and six in Condition 2.

Again most participants in Condition 3 mentioned the announcement as a trigger to take action (40%) as reflected in the last category 'announcement'. The effect of the smoke is not different between Conditions.

Question 6: Was there anything you were wondering or was there information lacking?

Table 3-10: Answers on question 6 in percentages of participants per Condition and in total

Condition	nothing	info in tunnel	info in general	simulation	radio	other
1	25%	30%	10%	40%	0%	0%
2	30%	20%	15%	15%	15%	5%

3	17%	28%	33%	6%	11%	6%
total	24%	26%	19%	21%	9%	3%

The answers to questions 6 fall into six categories. The first category 'nothing' consists of answers of participants that answered a simple “no” to the question or participants who answered with a blank. The second category 'info in tunnel' consists of answers that range from missing information on signs, indications for the emergency exits (even though emergency doors were present, also during the earlier rides that people had already made), information from loudspeakers/announcements, or what to do with the fire distinguishing equipment.

More specifically the six persons in condition 1 said the following:

1. Why are there no smoke detectors in the tunnel and lights that indicate emergency doors?
2. I saw the emergency door but it was not indicated by a light. I did not hear or see any signals
3. Should I have gone to the accident with a fire extinguisher? There was one there, I missed arrows to indicate the emergency doors.
4. Information through an announcement in the tunnel : mentioned by two people
5. Warning signs that tell you what to do

In condition 2 the four participants said the following:

1. No arrows or indication of emergency doors
2. Warning signs in the tunnel
3. Missed tunnel announcement
4. Why did everybody stay in their cars? Why were there no loudspeakers to tell you what to do?

Five participants in Condition 3 stated they missed information:

1. Information on the location of the emergency doors
2. The announcement should be more extensive
3. Warning through loudspeakers
4. Announcement in tunnel, what should people do in such a situation?
5. No signs in the tunnel why a traffic jam occurred. The participant offers the idea to use the tunnel walls.

The third category 'info in general' consists of answers in the realm of "what is going on?", "why are we stopping?", "how bad is it?", and "where do I go?". The fourth category 'simulation' consisted of answers of three people who wondered whether they should really get out of the car. The fifth category consisted of answers in relation to questions about the correct frequency for the radio to require information about situation, and people who did not hear any information via the radio, in spite of the fact that they were listing to the radio. The last category 'other' consisted of three answers:

1. Where were the police and firemen?
2. Realized something was wrong and would have called the alarm number (112)
3. The maximum speed was still 50 on the dynamic signage, and it took a long time before we have to turn off our engines.

About 24% of the participants did not think that information was lacking. These percentages differ only slightly between Conditions. Participants that did mention they specifically missed information in the tunnel was a total of 26%. Participants mentioning that they missed information in general because of not hearing a reason for the traffic jam, and the seriousness of the situation was a total of 19%.

Interestingly so, only people in Condition 2 and 3 mentioned that they wanted to listen to the radio or even tried to do so but did not hear any information about their situation on the radio or did not know the right frequency. In the leaflet (condition 2 and 3), information is provided to listen to messages on the radio.

The category 'simulation' includes answers that refer to discrepancies between the simulation and real world, for example "the lack of sound of approaching emergency vehicles" and "lack of sounds from other people or cars in the tunnel", or that they did not know whether they could actually leave the vehicle.

Question 7: Is there anything that you would have done differently in reality?

Table 3-11: Answers on question 7 in percentages of participants per Condition and in total

Condition	yes	maybe	no	probably not	others	other
1	35%	10%	25%	5%	5%	20%
2	10%	10%	40%	20%	15%	5%
3	40%	11%	22%	6%	6%	17%
total	29%	10%	29%	10%	9%	14%

The answers to question 7 fall into six categories. The first category 'yes' includes answers where participants say that they would have done something differently in reality, more specifically they would have gotten out of the car sooner. The second category 'maybe' includes answers of participants who mention that maybe they would have gotten out of their car sooner. The third category 'no' and the fourth category 'probably not' consist of exactly those two answers with one exception: 1 participants mentioned that if he would have smelled something he probably would have gotten out of his car sooner. The fifth category 'other' consists of answers of participants who mention they would have made sure that other people would be safe too (4 participants), or they would have waited longer to see what others would do (1 participant).

When asked if people would have done something differently in reality, 29% answered that yes, they would get out of the car sooner in real life and another 10% of the participants <u>thinks</u> that they might leave their car sooner in real life then they did now. An equal amount of participants said they certainly or probably would not have done things differently in real life. The category 'others includes answers of participants who mentioned that they would have either paid more attention to other people in real life as to what to do, or would make sure other people were safe too.

Question 8: Have you ever witnessed or been involved in an incident or accident in a tunnel?

Table 3-12: Answers on question 8 in percentages of participants per Condition and in total

Condition	no	yes
1	100%	0%
2	90%	10%
3	94%	6%
total	95%	5%

It can be concluded from the answers to this question that most participants had no experience with incidents in a tunnel before participating in the experiment. None of the three participants who had experience with an incident mentioned a fire or smoke incident. This means that participant had never encountered such a situation before.

Question 9: How do you normally experience driving through a tunnel (scary, not a problem at all, etc.)?

Table 3-13: Answers on question 9 in percentages of participants per Condition and in total

Condition	No problem		depends on		not comfortable / scary
	drive the same	drive differently	length	traffic	
1	35%	10%	20%	5%	30%
2	45%	5%	5%	10%	20%
3	39%	22%	11%	11	17%
total	40%	12%	12%	9%	22%

The answers to question 9 fall into three main categories of which two each have two subcategories. The first main category 'no problem' has the subcategories 'drive the same' and 'drive different'. The first subcategory includes answers of participants who say they have no problem with driving through tunnels and when doing so they drive the same as in any other situation. The second subcategory includes answers of participants who say they have no problem with driving through tunnels but when doing so they drive differently. They mention they are more nervous, look out for emergency exits, do not dare to overtake other cars, keep a more rigid lane position or are extra alert.
The second main category consists of answers of participants who say this either depends on the length of the tunnel (subcategory 1), or the amount of traffic in the tunnel (subcategory 2). The third main category 'not comfortable/scary' ranges from answers of participants who say they are glad when they leave the tunnel to people who say they always feel uncomfortable driving through tunnels.

As can be seen in Table 3-13, the majority of the participants do not report having any trouble driving through tunnels. A distinction is made between people who reports not having any problems and also report that they do not adapt their driving style (drive the same) and people who do not report having any problems with driving in a tunnel but who report changing their driving style in some way (drive different). A smaller group of participants reports having problems depending on the length of the tunnel or amount of traffic in the tunnel. 22% of the participants report being uncomfortable or scared when driving through a tunnel in the real world. This percentage is quite large, considering the number of people that drive through tunnels every day.

Question 10: Is there anything else you would like to mention?

Table 3-14: Answers on question 10 in percentages of participants per Condition and in total

Condition	No	simulation	other
1	35	35	30
2	50	40	10
3	55.5	33.3	22.2
Total	46.6	36.2	20.7

The answers to question 10 fall into three categories. Most participants (almost half of them) either filled in a blank or 'no' in response to this question (category 1: 'no'). The second category 'simulation' consists of answers of participants who mention something in relation to the fact that it was a simulated event. For example that they thought the steering and/or braking of the simulated car was different (13 out of 21); or, that the simulation was very realistic and good for practice (3 participants). The category 'other' consisted of a mix of answers ranging from: 'fun experience', to tips on how to improve tunnel-safety. These were:

Is there room for emergency vehicles? (condition 1)

Signs with “50” could be misleading, should be “traffic jam”(condition 1)

There are enough fire extinguishers and telephones but no sign what to do or where to go in emergency situation. (condition 1)

There is a lot of attention for tunnel safety, but I think that Dutch tunnels are fairly safe (condition 1) (note: the fact that people think it safe might mean they don't take action!!)

I missed an alarm warning signal so people would react immediately (condition 2)

Better information in tunnel (matrix signs); what is going on? How long will it take? Which evacuation route? (condition 2)

More information on what to do and where to go (condition 3)

Make third breaking light and day-time-running lights obligatory (condition 3)

Miss safety zone for people; where should they walk? (condition 3)

Make entrance and exit lanes longer, emergency lights are used too late (condition 3)

3.1.3 Discussion and Conclusions

We can conclude there are indeed some differences between the conditions.

About 60% of the drivers switch off the engine spontaneously, after reading the leaflet this increases to 70%, only with the help of the operator this number rises to 100%. Also, time passing after coming to a stop was longer if people did not read the leaflet and were shortest if people heard the operator voice. Not too many people use the radio to get additional information, not even after reading the leaflet. The most crucial action, that is getting out of the vehicle (or stating one would), is highly affected by the statement of the operator. Whereas 65% of the people indicate they would want or try to leave the vehicle, with 75% of the people who read the leaflet, this number increases to 94% after the operator announcement. So reading the leaflet already improves the situation somewhat compared to not getting any additional information. However, with the help of an operators' voice, performance improves even more. This leads to more people doing the right thing, but also to getting into action more quickly.

Some people specifically mentioned that they planned to walk back to the entrance of the tunnel instead of using the emergency doors, which they were required to do, specifically people without any additional information. Since all subjects already drove the tunnel 3 times before and had a chance to see the exits inside the tunnel on ride 4 as well, apparently some people still want to use the tunnel entry as an exit. In the last group, in which it is specifically mentioned by the operator, no-one mentioned this. This indicates that it is indeed a matter of receiving the appropriate information. Also, the use of radio information is difficult, even though some people specifically mentioned that they knew they had to use the radio for specific messages, they forgot what frequency (a specific frequency is mentioned in the leaflet). So in case there would be a radio message, it should be broadcasted via all radio channels.

What remains an important area is that quite some people indicate they do not have an idea of how to handle in the given situation (even in the condition with leaflet and operator). This means that there is a lot of uncertainty in the case of accidents or incidents in tunnels, and even though there is an operator voice, even though people read the leaflet, there is still uncertainty how to behave. This is something we have to be aware of in the near future: even though designers may think that all information needed is there, this may not be enough for the road users. Information provided needs to be over-complete, with if possible a repetition of the messages. Also, people with visible official status should be sent inside the tunnel in order to help people make the right decisions. Also, as was also discussed in the PIARC committee, we need to have people with an exemplary behavioural function, for instance professional drivers. Since these people drive tunnels more often than the average driver, their behaviour might influence other road users to do the same. It is interesting to compare these results from normal car drivers with the results of the driving simulator study of truck drivers done by SINTEF to see if indeed this group of drivers handles more properly because of this exemplary function.

When looking at the questionnaires, the 2 people who stated they thought there was a motor problem with another car did not act adequately for a fire. They did not turn off their engine, nor left their vehicle. This may also be interpreted that if people do not understand the urgency, they do not act accordingly.

Almost all participants (over all categories an average of 83%) mentioned the smoke as an indicator for them to understand what had happened in the tunnel (independently of whether their understanding of the situation was correct). The fact that the smoke intensified or that it occurred in combination with a traffic jam was important for almost half of that group to determine what was going on. Since the traffic jam occurred earlier in time than the appearance of the smoke one can say that participants mentioning the traffic jam as a reason to understand what was going on were sooner concerned or alarmed than the participants merely mentioning the smoke. No major differences between Conditions could be observed.

When we asked people what made them decide to take action (or why they did not take action) , two participants in Condition 2 did not take action because of the smoke. One person said the smoke was too thick to approach the accident. The other person said the smoke was not very thick and that he therefore did not see any reason to go out of the car. This clearly shows that the interpretation of information is highly personal. Providing information such as: ‘If the smoke gets thick, please leave the vehicle’ would not make any sense since the definition of thick smoke varies from person to person. Even after reading the leaflet some persons mentioned that they were waiting for a signal or information on the radio to leave the car (even though the leaflet says: Smoke and fire can kill). Even if the operator informed road users, one person mentioned that it was unclear where to go and one person indicated to need more clarity of how to respond.

One of the good results of reading the leaflet may be that no-one after reading the leaflet mentioned that they did not take any action because they waited for others to take action (3 people indicated this without reading the leaflet). One person specifically mentioned he knew what to do due to the leaflet. One person (without reading the leaflet) mentioned he felt safer in the car and one person (even after hearing the operator) simply mentioned that he wanted to get out but was afraid to do so. The fact that a lot of people mentioned the smoke as the reason to take action, we have to be careful with getting the smoke completely out of the tunnel: this may enhance the delay in response time. However, that reading the leaflet is not enough is shown by the people who said that they did not take any action (e.g. because they did not want to panic, did not see any panic, tried to stay calm, were looking for more information etc) even though they read the leaflet. There were only less people stating that is was not necessary to respond in the category where the operator stated what to do.

Even in the condition that an operator announced switching off the engine and getting to the emergency exits, people though information was lacking. In general, remarks were made about necessity to light emergency doors, warnings signs, information about what is going on, how serious it is and what to do, the need for information to be more extensive or information on the radio (this was only mentioned by people reading the leaflet, so apparently this is something they remembered without remembering the frequency). About a quarter of the people did not think any information was lacking.

At the end of the study, some drivers gave some tips on how to improve traffic safety, these were general remarks about the Dutch traffic signaling system (which is curious since this is the way it works in real life), place signs on what is going on and what needs to be done instead of only placing telephones and fire extinguishers, and put an alarm warning signal.

3.2 Truck Driving Simulation

The SINTEF study also focused on the effects of the EU tunnel leaflet on driver's perception of the situation in terms of risk and coping, but this time the subjects included in the experiment were truck drivers. The aim was also to investigate how information affects they way that truck drivers ideally deem to handle the occurring incident during the experiment.

Important issues that were focused in this study were:

- How do truck drivers perceive, cope and behave in a tunnel fire incident?
- Is there a difference in driver behavior and response to fire incidents between informed drivers (who have read the EU leaflet) and non-informed drivers?

To answer the questions about truck driver behavior in tunnel fire incidents a representative sample of truck drivers were exposed to a tunnel scenario with a fire incident in the SINTEF advanced driving simulator. To answer the second question half of the truck drivers in the sample were asked to read the EU leaflet on tunnels prior to their ride in the simulated tunnel environment.

3.2.1 Method

<u>Participants</u>

In the SINTEF study, 42 male truck drivers participated, with an average age of 41 (varying from 24 to 59 years of age). The drivers had their truck drivers license 21 years on average (varying from 4 to 42 years). Their average driver experience was self reported and varied from 15.000 to 20.000 kilometers per year. Two professional fire fighters with truck driver license were included in the sample of 42 drivers. The drivers reported normal health and no phobias or similar disorders.

<u>Apparatus</u>

The SINTEF Driving Simulator is a 'high-end simulator' based on a full scale and fully equipped Renault Magnum truck cabin with an integrated seat motion system. Five channels of visual information provide the Field of View (FoV). The three front screens are rear projected and provide in sum 180 degrees horizontal FoV and 47° vertical FoV. The two screens behind the vehicle are front projected and supply in sum 90° vertical FoV and 47° vertical FoV each (see 16 and 17):

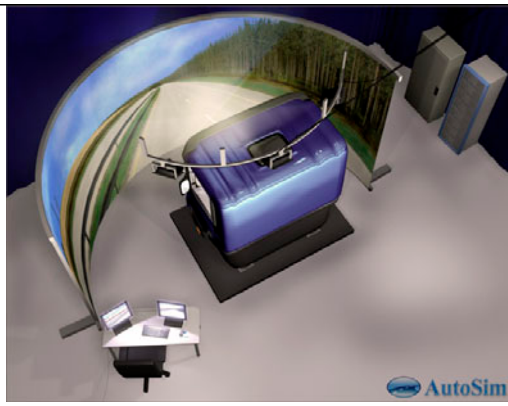


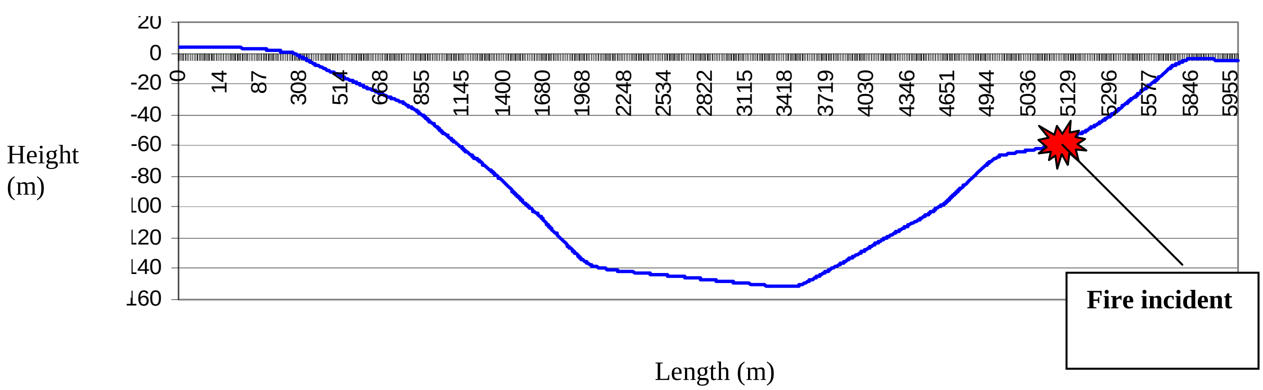
Figure 3.3: Sintef Truck Simulator Setup

Figure 3.4: Sintef Truck Simulator

Scenario

The chosen scenario for presentation of experimental conditions is a 3D model of the “Froya” sub sea tunnel in Norway. The tunnel is characterized by a downhill decent towards the lowest underwater level, followed by a horizontal segment with no gradient, then the rise towards the surface in the latter part of the
tunnel.

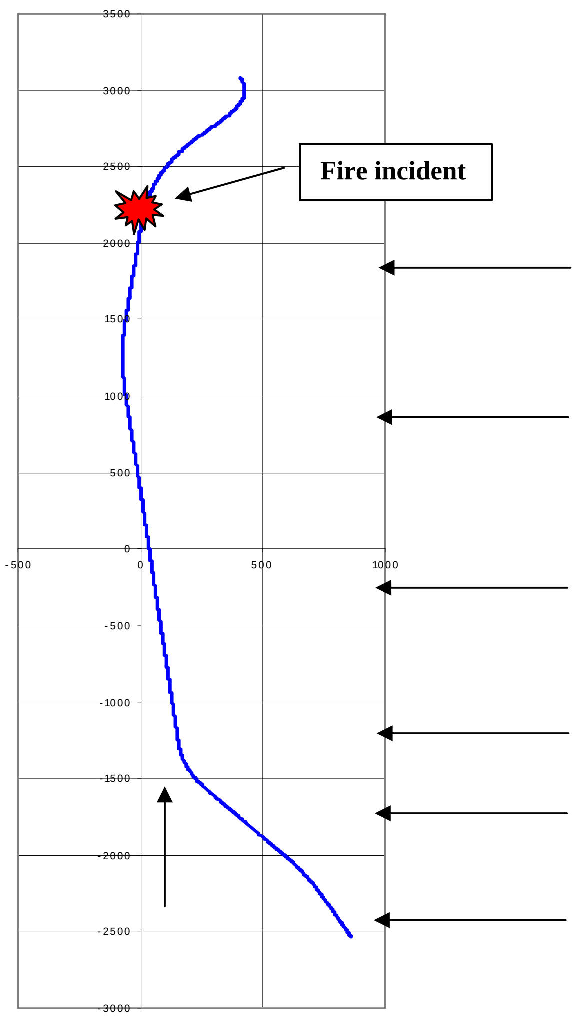
Frøya tunnel: Vertical alignment



The Frøya tunnel is 5.3 kilometers long and contains safety features as SOS stations, turning points (regular and large), ventilation fans, road signs indicating the position in tunnel. The tunnel scenario contains approximately 300 meters of highway driving before and after the tunnel. Automated vehicles provide a moderate oncoming traffic flow during drive. The scenario was further marked with a segment variable, enabling analysis on isolated parts of the scenario. This allows for more detailed investigation of driver performance in specific types tunnel road environments.

The UPTUN Tunnel Incident Scenario was divided into six segments:
Segment 1: Tunnel entrance, beginning of downhill slope
Segment 2: Mid part of downhill, slight right curve
Segment 3: Latter part of downhill, straight road
Segment 4: Straight road, no curve or gradient change
Segment 5: Beginning of rise toward surface. In the fire scenario, there was a first sight of smoke.
Segment 6: Latter part of tunnel, uphill. The fire accident was located in this segment.

Frøya tunnel: Horisontal alignment



Segment 6: Latter part of tunnel, uphill. Fire accident is located in this segment.

Segment 5: Beginning of rise toward surface. In fire scenario, first sight of smoke.

Segment 4:Straight road, no curve or gradient change

Segment 3:Latter part of downhill, straight road

Segment 2:Midpart of downhill, slight right curve

Segment 1:Tunnel entrance, beginning of downhill slope

Material: Tunnel fire incident

The SINTEF UPTUN scenario presents a dynamic 3D rendering of a tunnel accident simulating an impact between a truck and a car in the middle of the road. The fire consists of a combination of two animated objects: one object renders fire, the other provides the adherent smoke (See Figure 3.5). There was no other traffic in the area around the fire incident. This avoids other vehicles cueing up around the incident and hence disturbs the driver.

Figure 3.5: The Sintef UPTUN Tunnel Incident

Visibility and distance to the accident object were configured as a linear relationship in which the visibility deterred as the driver came closer to the accident. The configuration gave the following combinations:

Table 3-15: Relationship between distance and visibility

Distance (metres)	Line of Sight(metres)
1000	330
500	180
300	121
182	83,5
100	55,3
40	40

This mean the visibility became very poor when closing up to the incident.

For the test drive, the participants drove on an open landscape highway containing low density traffic.

Figure 3.6: Test drive scenario

Procedure

The participants were given one initial practice drive in order to acquaint themselves with the driving simulator situation. The practice drive lasted approximately ten minutes, until the driver said he felt comfortable enough in the simulator and that he by now was ready to start the experiment.

The experimental conditions were presented in a fixed order, applying a between-subject design.

First, the truck drivers drove the tunnel without any incidence or abnormal activity occurring. The instruction was to drive to the tunnel and stop just outside the end of tunnel on the other side.

Finally, they drove the same tunnel with the tunnel fire incident occurring 4700 meters inside the tunnel. The trial ended when the driver had stopped the truck and turned off the engine. The instruction was identical to the first trial, where they were simply told to drive through and stop at the other side.

Objective measures

Objective measures were obtained in both experimental conditions. The sampling was done in a 20 Hz rate during the entire drive. The simulator sampled a number of variables related to the driver performance.

- Speed (in kilometers per hour)
- Use of Pedals: Brake and accelerator (1 equals full throttle and zero equals no throttle)
- Steering wheel angle (ranging from -1 indicating far left to 1 indicating far right)
- Vehicle position on the road (measured in meters from the lane center, a positive value refers to road center, a negative value refers to off center lane perimeter)
- Distance to other vehicles (in meters from vehicle center to objects in front). This measure was only obtained in relation to the fire incident during the drivers second drive

Based on the raw data from the 20 hz sampling from the simulator, aggregated values for each driver in each segment was calculated in both normal and fire incident drive. This data was used as basis for the statistical analysis of differences and descriptives.

Background information and subjective measures

Background information included demographic data, drive style, health status, phobia screening. The information was retrieved in a briefing and debriefing questionnaire.

The subjective measures included mental workload (NASA RTLX), risk perception, memory recall items, and semantic differentials questionnaires. The information was obtained by questionnaires after each simulator trial. NASA Retrospective Task Load Index (Hart & Staveland, 1988), measured 6 aspects of subjective workload; mental, physical, time pressure, performance, effort and frustration. The NASA RTLX is a subjective rating procedure that provides an overall workload score based on a weighted average of ratings on six sub scales.

Each scale is presented with a short text relating the item to the relevant task. The subject then rates the item from 0 to 100 on a continuous scale, with 0 indicating no load at all, and 100 indicating the highest load.

In addition, video recordings of the experiment were obtained, showing in vehicle driver reactions during the trials (see Figure 3.7).

Figure 3.7: Video of driver during trials

Experimental design

The study applied a between subject design, in which both groups of drivers drove the two experimental scenarios in a fixed order after the initial test drive.

Group 1 (N=21) was presented the EU information leaflet after the test drive and before first experimental condition. The leaflet was introduced as information material provided by the government, in which the participant was encouraged to read through.

Group 2 (N=21) received no additional information.

First, they drove the “no-incident” tunnel scenario. Then they drove the scenario with the fire accident.

3.2.2 Results

The data was analyzed with SPSS for Windows v.12.0.

The number of valid log files from the simulator is 42 in the first experimental drive (normal conditions) and 40 in the second drive (fire incident condition). Two log files were incomplete due to simulator system failure during trials. Further, one log file was incomplete for segment 6, leaving 39 valid files for that segment.

<u>Speed in the different segments</u>

Speed levels were logged during the simulator drive, and the results were distributed as follows:

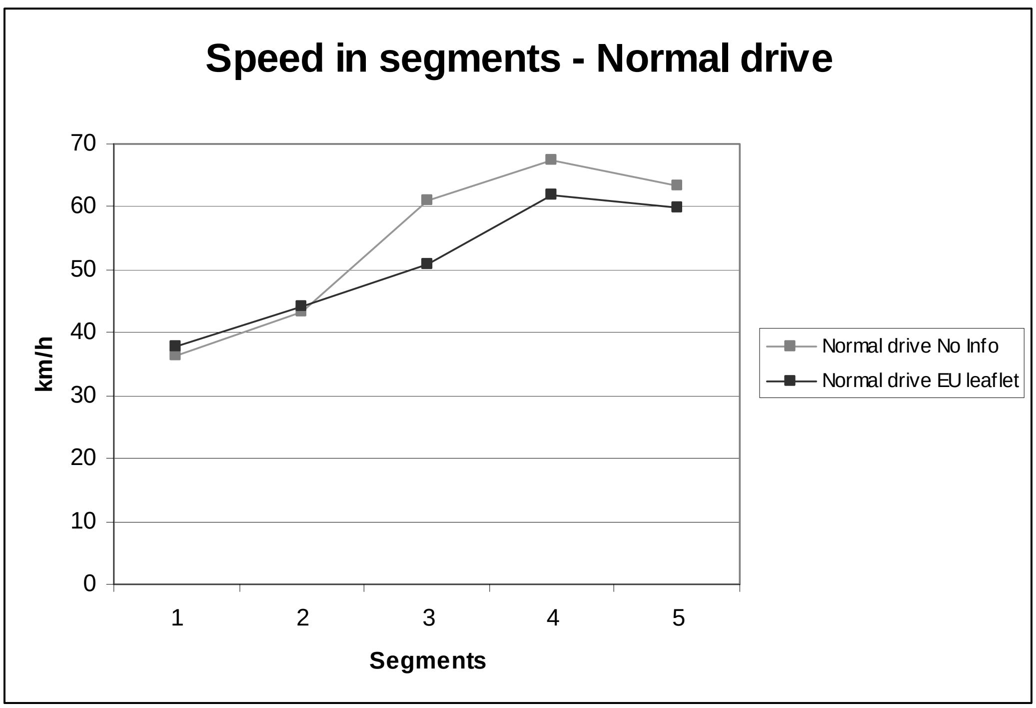


Figure 3.8: Speed levels of experimental conditions in normal drive

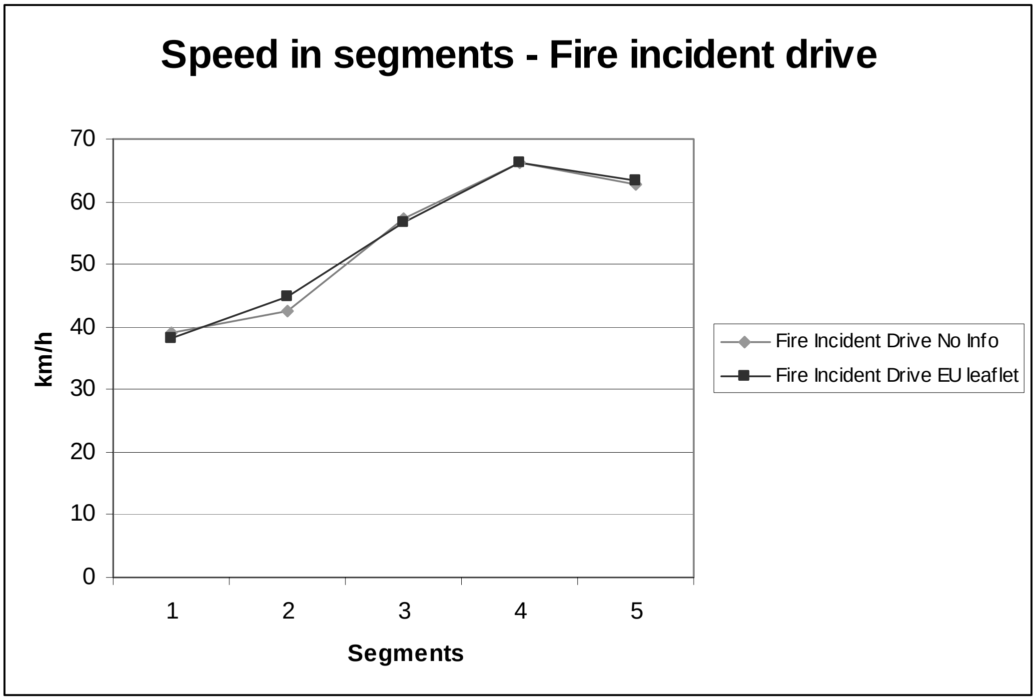


Figure 3.9: Speed levels of experimental conditions in fire incident drive

The data at base for the figures are presented below:

Table 3-16: Mean values of speed in km/h for experimental groups

Segments	Normal drive		Fire Incident Drive	
	No Info	*EU leaflet*	*No Info*	*EU leaflet*
1	36,19	37,81	38,98	38,24
2	43,27	44,22	42,48	44,9
3	61,00	50,76	57,26	56,67
4	67,35	61,88	66,21	66,26
5	63,46	59,86	62,89	63,24

T-test showed no significant differences in speed levels between the groups in either condition.

Objective variables for segment 1

Descriptive statistics were obtained for each segment. Segment 1 marks the tunnel entrance and the beginning of the downhill slope towards the lowest underwater level. The traffic density is low. The data from simulator log file was distributed as follows:

Table 3-17: Descriptives for segment 1 - first drive with no incident

Seg 1 Normal		Km/h mean	Km/h SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	36,19	5,66	-1,48	,10	,0172	,0447
	N	22	22	22	22	22	22
EU leaflet	Mean	37,81	5,11	-1,50	,08	,0129	,0310
	N	20	20	20	20	20	20
Total	Mean	36,96	5,40	-1,49	,09	,0152	,0382
	N	42	42	42	42	42	42
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,0000	,0000	,0347	,0754		
	N	22	22	22	22		
EU leaflet	Mean	,0000	,0000	,0497	,0897		
	N	20	20	20	20		
Total	Mean	,0000	,0000	,0419	,0822		
	N	42	42	42	42		

Table 3-18: Descriptives for segment 1: Drive with fire incident

Seg 1 Fire		Km/h mean	Km/h SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	38,98	3,15	-1,54	,09	,0164	,0257
	N	21	21	21	21	21	21
EU leaflet	Mean	38,24	4,35	-1,53	,11	,0100	,0233
	N	19	19	19	19	19	19
Total	Mean	38,63	3,72	-1,54	,10	,0134	,0245
	N	40	40	40	40	40	40
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,0704	,0348	-,0006	,0026		
	N	21	21	21	21		
EU leaflet	Mean	,0195	,0381	-,0008	,0047		
	N	19	19	19	19		
Total	Mean	,0463	,0363	-,0007	,0036		
	N	40	40	40	40		

T-tests of the values showed no statistical significant differences in either of experimental scenarios.

Objective variables for segment 2

Segment 2 marks a slight right curve in the tunnel downhill. Traffic density is still low. The data from the log file were distributed as follows:

Table 3-19: Descriptive variables for segment 2 - normal drive

Seg 2 Normal		Km/h mean	Km/h SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	43,2743	3,6589	-1,381258	,143373	,025978	,048255
	N	22	22	22	22	22	22
EU leaflet	Mean	44,2208	3,0740	-1,403660	,134535	,025461	,040798
	N	20	20	20	20	20	20
Total	Mean	43,7250	3,3804	-1,391926	,139165	,025732	,044704
	N	42	42	42	42	42	42
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,000000	,000000	,046933	,017725		
	N	22	22	22	22		
EU leaflet	Mean	,000000	,000000	,009294	,016419		
	N	20	20	20	20		
Total	Mean	,000000	,000000	,029010	,017103		
	N	42	42	42	42		

Table 3-20: Descriptive variables for segment 2 - fire incident drive

Seg 2 Fire		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	42,4821	2,3182	-1,459034	,122618	,018230	,026098
	N	21	21	21	21	21	21
EU leaflet	Mean	44,9092	2,9463	-1,438915	,132141	,021320	,034396
	N	19	19	19	19	19	19
Total	Mean	43,6349	2,6166	-1,449478	,127142	,019698	,030039
	N	40	40	40	40	40	40
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,059319	,033347	,005840	,003967		
	N	21	21	21	21		
EU leaflet	Mean	,004811	,014628	,005821	,004337 (*)		
	N	19	19	19	19		
Total	Mean	,033428	,024456	,005831	,004143		
	N	40	40	40	40		

A T-test was performed in order to investigate differences. No statistical significance was found in either of the experimental scenarios. Yet, a tendency was seen in the fire incident condition on differences in standard deviation in steering wheel angle ($p<.086$ and $t=-1.763$). This indicates that there is a tendency for the group who had read the EU leaflet towards more steering wheel movement during the fire incident drive in this segment, although it does not reach statistically significant differences. The interpretation of this can lead to several possibilities, as will be assessed in the discussion.

Objective variables for segment 3

Segment 3 marks the last part of the downhill decent towards lowest underwater level of the tunnel. The road is straight and levels out in the latter part of the segment. The objective measures were distributed as follows:

Table 3-21: Objective variables for segment 3 - normal drive

Seg 3 Normal		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	61,0026	9,7470	-1,413146	,130075	,011418	,033545
	N	22	22	22	22	22	22
EU leaflet	Mean	50,7644	8,2116	-1,465680	,092245	,012527	,040901
	N	19	19	19	19	19	19
Total	Mean	56,2581	9,0355	-1,437491	,112544	,011932	,036954
	N	41	41	41	41	41	41
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,000000	,000000	,364411	,318286		
	N	22	22	22	22		
EU leaflet	Mean	,000000	,000000	,387740	,351540		
	N	19	19	19	19		
Total	Mean	,000000	,000000	,375222	,333696		
	N	41	41	41	41		

Table 3-22: Objective variables for segment 3 - fire incident

Seg 3 Fire		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	57,2673	10,3271	-1,464008	,117314	,007476	,025043
	N	21	21	21	21	21	21
EU leaflet	Mean	56,6791	8,3906	-1,473970	,107148	,007377	,027592
	N	19	19	19	19	19	19
Total	Mean	56,9879	9,4073	-1,468740	,112485	,007429	,026254
	N	40	40	40	40	40	40
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,371383	,332896	,000051	,002341		
	N	21	21	21	21		
EU leaflet	Mean	,353053	,327072	,000026	,002056		
	N	19	19	19	19		
Total	Mean	,362676	,330130	,000039	,002205		
	N	40	40	40	40		

A T-test of the data showed no statistically significant differences in either condition. However, a tendency was seen in the normal drive condition on the values of standard deviation in lateral position ($p<0.58$ and $t=1.950$). This indicates that the group with no extra information tended to swerve more in their lane during the normal drive in segment 3.

Objective variables for segment 4

Segment 4 marks the horizontal stretch at the tunnel midparts. The road is straight with low traffic density. The objective measures were distributed as follows:

Table 3-23: Objective variables for segment 4 - normal drive

Seg 4 Normal		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	67,3515	2,3608	-1,434376	,113718	,000850	,001135
	N	22	22	22	22	22	22
EU leaflet	Mean	61,8895	1,8221	-1,475309	,095507	,000000	,000000
	N	20	20	20	20	20	20
Total	Mean	64,7505	2,1043	-1,453868	,105046	,000445	,000595
	N	42	42	42	42	42	42
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,000000	,000000	,643682	,169900		
	N	22	22	22	22		
EU leaflet	Mean	,000000	,000000	,695391	,137532		
	N	20	20	20	20		
Total	Mean	,000000	,000000	,668305	,154487		
	N	42	42	42	42		

Table 3-24: Objective variables for segment 4 - fire incident drive

Seg 4 Fire		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	66,2104	1,9811	-1,482648	,103876	,000000	,000000
	N	21	21	21	21	21	21
EU leaflet	Mean	66,3679	2,1298	-1,505885	,106578	,000000	,000000
	N	19	19	19	19	19	19
Total	Mean	66,2852	2,0518	-1,493686	,105160	,000000	,000000
	N	40	40	40	40	40	40
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,710491	,151708	-,000178	,001667		
	N	21	21	21	21		
EU leaflet	Mean	,668691	,159445	-,000205	,001906		
	N	19	19	19	19		
Total	Mean	,690636	,155383	-,000190	,001781		
	N	40	40	40	40		

T-tests showed no statistical significant differences between the experimental conditions in either the normal drive or the fire incident drive.

Objective variables for segment 5

Segment 5 marks the last part of the horizontal stretch and the beginning of the rise towards the tunnel exit at surface level. The objective variables were distributed as follows:

Table 3-25: Distribution of objective variables, segment 5 - normal drive

Seg 5 Normal		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	63,4656	2,6385	-1,386937	,148577	,000000	,000000
	N	22	22	22	22	22	22
EU leaflet	Mean	59,8679	1,9332	-1,426015	,129471	,000000	,000000
	N	20	20	20	20	20	20
Total	Mean	61,7524	2,3026	-1,405546	,139479	,000000	,000000
	N	42	42	42	42	42	42
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,000000	,000000	,885328	,115256		
	N	22	22	22	22		
EU leaflet	Mean	,000000	,000000	,903687	,089557		
	N	20	20	20	20		
Total	Mean	,000000	,000000	,894070	,103018		
	N	42	42	42	42		

Table 3-26: Values of objective variables in segment 5 - fire incident drive

Seg 5 Fire		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	62,8906	2,3132	-1,447524	,140153	,000000	,000000
	N	21	21	21	21	21	21
EU leaflet	Mean	63,2462	4,0141	-1,441738	,129131	,003534	,011932
	N	19	19	19	19	19	19
Total	Mean	63,0595	3,1211	-1,444776	,134918	,001679	,005668
	N	40	40	40	40	40	40
		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD		
No info	Mean	,878571	,124939	,001309	,002503		
	N	21	21	21	21		
EU leaflet	Mean	,842796	,159824	,001301	,002835		
	N	19	19	19	19		
Total	Mean	,861578	,141509	,001305	,002661		
	N	40	40	40	40		

T-tests indicated no statistically significant differences between the experimental groups in either drive. Yet, some tendencies were seen in the fire incident drive. The drive group with the EU leaflet had a slightly higher value of standard variation of speed than the group without info ($p<.099$ and $t=-1.689$). This indicates that the drivers with EU leaflet tended to vary their speed more during the fire incident drive in this segment than the group without info.

Objective variables for segment 6

Segment six contained the fire incident providing the experimental condition. The results of the first normal drive are not comparable due to occurrence of fire incident in the segment. Further, only data for the last kilometer before fire incident location are included in order to collect data relevant for the experience of approaching the accident.

The results from the second drive were distributed as follows:

Table 3-27: Objective variables from segment 6, last kilometer before fire incident

Seg 6 Fire		Km/h mean	Kmh SD	Lateral mean	Lateral SD	Brake Mean	Brake SD
No info	Mean	15,6579	17,7487	-1,339491	,409931	,152898	,200142
	N	21	21	21	21	21	21
EU leaflet	Mean	12,7663	17,7438	-1,058012	,442194	,109429	,205106
	N	18	18	18	18	18	18
Total	Mean	14,3233	17,7465	-1,209578	,424822	,132836	,202433
	N	39	39	39	39	39	39

		Accelerator Mean	Accelerator SD	Steering Wh Mean	Steering Wh SD
No info	Mean	,181197	,263100	-,023982	,032820
	N	21	21	21	21
EU leaflet	Mean	,118768	,214381	,000673	,008071
	N	18	18	18	18
Total	Mean	,152383	,240615	-,012603	,021397
	N	39	39	39	39

T-tests showed no statistically significant differences between the experimental groups.

Fire Incident: Minimum distance to accident and driver behaviour

The participants were presented the fire incident in the second drive, by way of a simulated car accident. The minimum length from the interactive vehicle brought to full stop to the accident was logged.

Eight of the 39 participants either drove past the fire incident directly or crashed into the objects on fire on slow speeds. The data of three participants were missing due to simulator system failure during the experiment. However their behavior was recorded on video. The video does not allow for exact position measurement, but allows categorizing behavior.
The data for distance to accident were as follows:

Table 3-28: Minimum distance from vehicle in full stop to fire incident

Seg 1 Normal	N	Distance to fire Mean	Distance to fire SD
No info	17	16,23	8,76
EU leaflet	14	20,23	15,89
Total	31	18,04	12,43

T-test showed no statistically significant difference between the groups in terms of minimum distances from interactive vehicle to fire incident location.

The results on truck driver behavior (Figure 3.10) show that 17 drivers (40%) stopped and parked their vehicle at a safe distance from the burning vehicles in the tunnel. The rather low number of subjects stopping in time may be due to the very low visibility close to the fire incident. The majority of the drivers drove too fast when taking the actual visibility under consideration. 14 drivers (33%) stopped right beside the fire incident. Post test interviews of the all drivers who stopped indicated they the intention of leaving their vehicle to run or walk out of the tunnel. Three drivers activated the Hazard Warning lights before leaving their parked vehicle. None of the drivers expressed any intention of trying to extinguish a fire of the present magnitude. The mean speed of vehicles passing the fire incident was 24 km/h with a min/max speed of 3.5 km/h and 49.3 km/h. For the two drivers who were unable to stop in time and collided with the burning vehicles their speed were respectively 82.3 km/h and 94.6 km/h, prior to braking. The speed limit in the real tunnel as well in the simulated virtual model of the tunnel is 80 km/h. The subjects were informed of the speed limit.

The data for truck driver behavior for different groups were as follows:

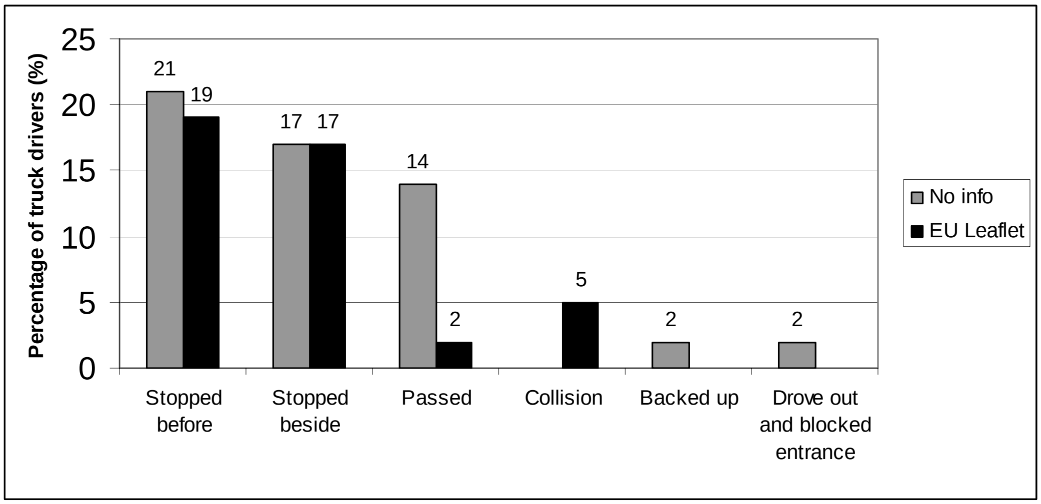


Figure 3.10: Driver behavior in fire incident for different groups

The behavior exposed by the different groups showed some group differences. Of the truck drivers who stopped before or beside the fire incident two from the EU Leaflet group activated their Hazard Warning Lights before leaving their parked vehicle and one from the no info group. The only marked difference is that six drivers (14%) of the no info group passed the fire incident (2 % did this in the info-group), and that two drivers (5 %) of the EU leaflet group collided with the vehicles on fire, unable to regulate their distance (whereas this was 0% in the no info group). The two professional fire fighters (one driver in each group) stopped before the fire at respectively 17 and 9 meters distance. The fire fighter stopping at 17 m was in the EU leaflet group.

Subjective measures: NASA RTLX

NASA RTLX was administered during the simulator trials. First, in relation to how the drivers experienced driving in normal, everyday settings. The test was also administered after each experimental condition.

The results were distributed as follows:

Table 3-29: NASA RTLX - Normal drive

Normal drive	Mental	Physical	Time	Performance	Effort	Frustration
No info	61,77	44,50	45,09	72,73	54,68	35,88
EU leaflet	65,90	37,20	36,11	65,15	53,80	32,15

Table 3-30: NASA RTLX - Test drive

Test drive	Mental	Physical	Time	Performance	Effort	Frustration
No info	78,18	38,55	28,82	33,00	64,09	44,27
EU leaflet	74,45	46,65	33,30	32,95	63,85	47,60

Table 3-31: NASA RTLX - No incident

No incident	Mental	Physical	Time	Performance	Effort	Frustration
No info	63,09	38,64	25,95	57,00	60,82	34,27
EU leaflet	63,15	44,75	27,20	58,10	55,60	31,60

Table 3-32: NASA RTLX - Fire incident

Fire incident	Mental	Physical	Time	Performance	Effort	Frustration
No info	63,29	42,76	28,86	52,57	56,38	36,05
EU leaflet	59,58	37,16	25,79	59,42	58,42	32,16

A T-test showed no significant differences between the groups in none of the conditions.

Subjective measures: Risk Perception

A schema for risk perception was administered after the fire incident drive. The risk perception questionnaire included 10 items, probing various aspects of risk. High scores indicate high level of concern, whereas low scores indicate low concern.

The distribution was as follows:

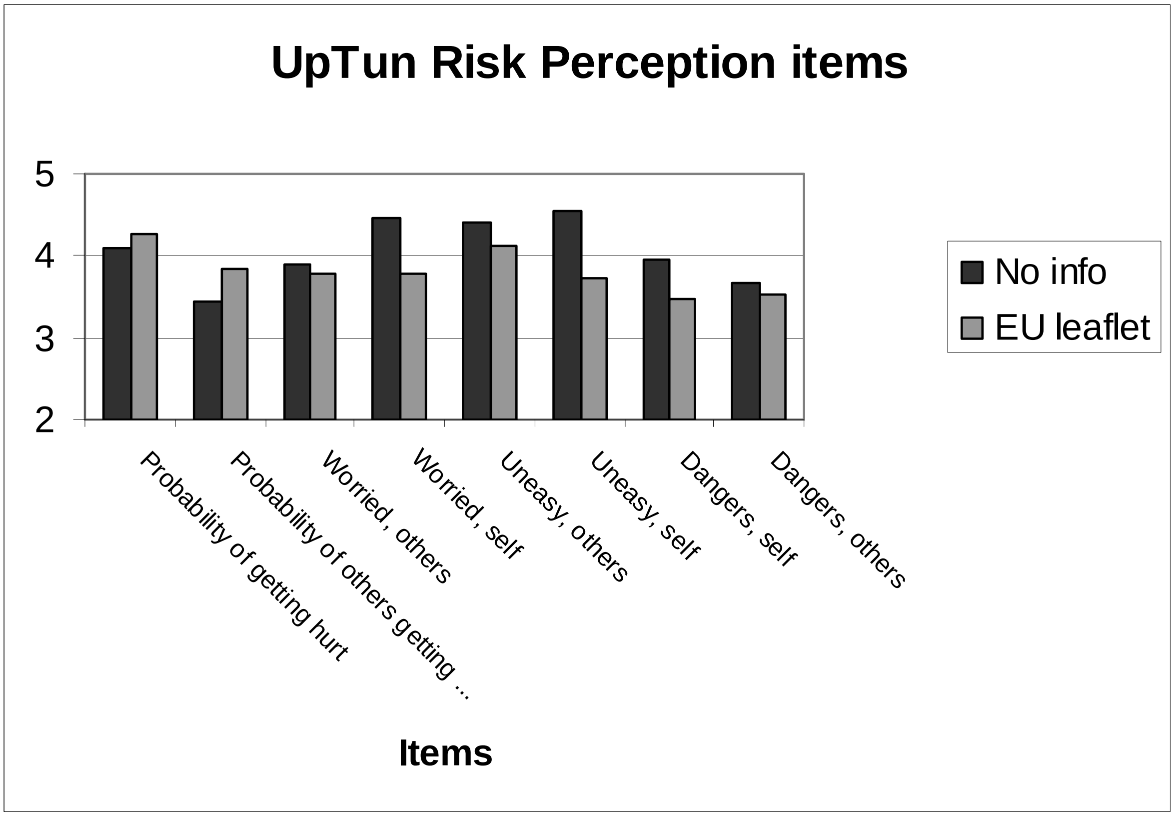


Figure 3.11: UPTUN Risk Perception Items

Table 3-33: Risk Perception Items

Risk Perception Items	No info	EU leaflet
Experience of probability of own accident involvement	4,10	4,26
Experience of probability of other accident involvement	3,45	3,84
Worry for other drivers accident involvement	3,91	3,79
Worry for own involvement of accident involvement	4,45	3,79
Uneasy for other drivers being hurt in accidents	4,41	4,11
Uneasy for being hurt in accidents	4,55	3,74
Thinking about the danger of tunnels for one self	3,95	3,47
Thinking about the danger of tunnels for others	3,68	3,53

A T-test showed no significant differences between the groups in any of the items.

<u>Subjective measures: Semantic Scales</u>

The risk perception questionnaire included two semantic differentials in which adjectives were paired for the drivers to define their tunnel experience. One for which the dangers of driving through a tunnel was assessed, the other was specifically related to the tunnel fire incident occurring in the scenario.

The scale range from 0, marking the positive aspect, to 6, marking the negative aspect. The distribution was as follows:

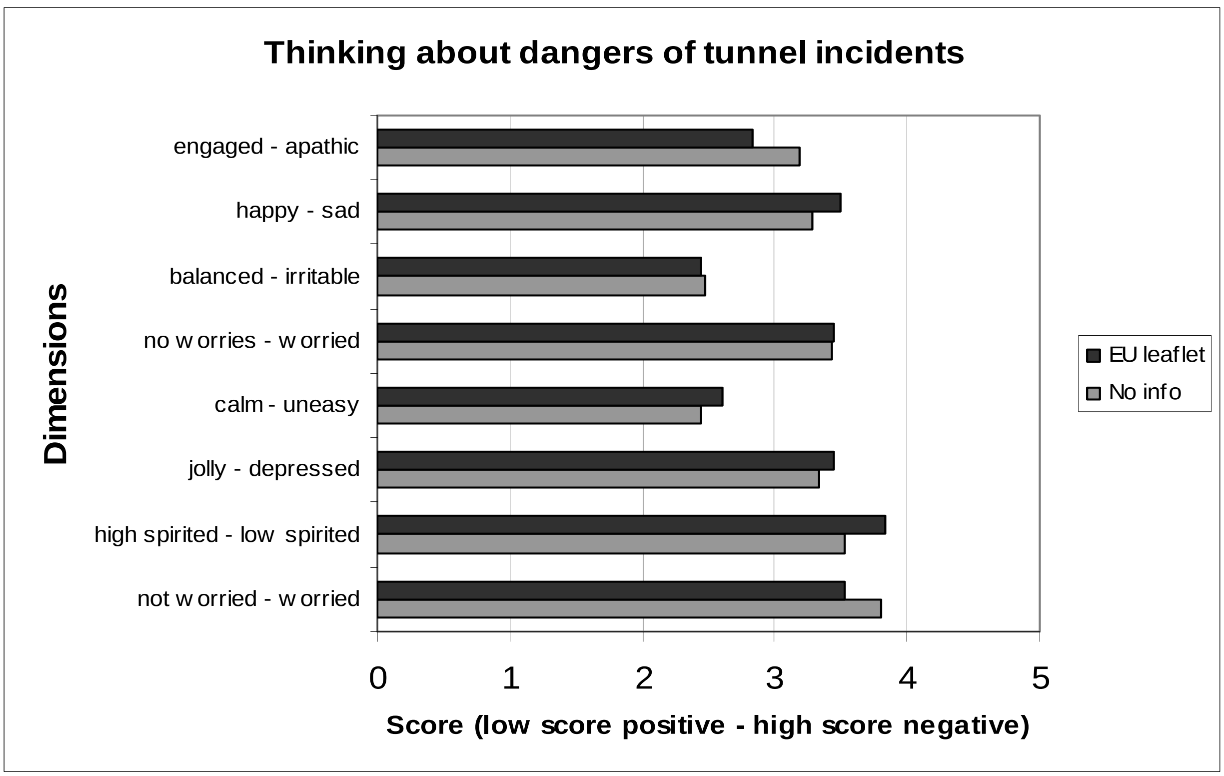


Figure 3.12: Semantic differential - Emotional aspects

Table 3-34: Semantic differentials

Semantic differential for tunnel experience	No info	EU leaflet
not worried – worried	3,81	3,53
high spirited - low spirited	3,52	3,83
jolly – depressed	3,33	3,44
calm – uneasy	2,45	2,61
no worries – worried	3,43	3,44
balanced – irritable	2,48	2,44
happy – sad	3,29	3,50
engaged – apathic	3,19	2,83

A T-test gave no significant group differences.

A schema assessing the experience of the tunnel drive in terms of semantic differentials was administered after final drive.

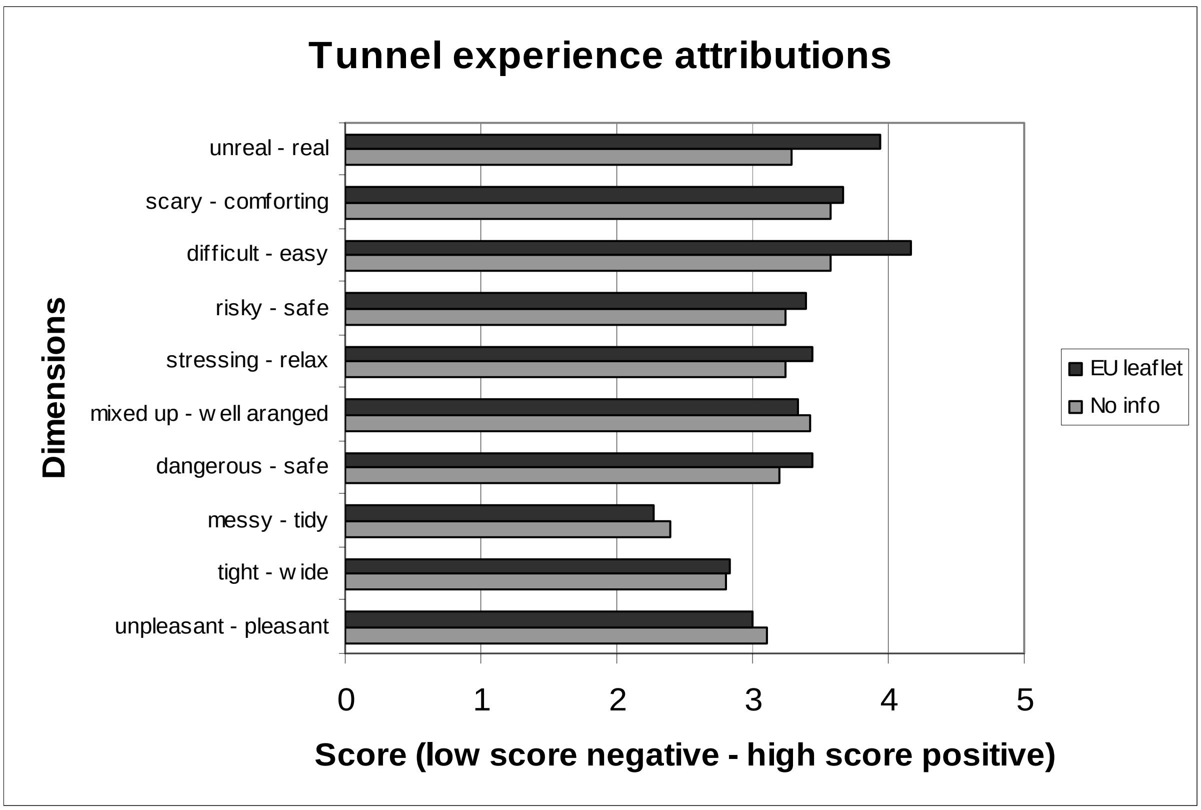


Figure 3.13: Tunnel experience

Table 3-35: Semantic differential for tunnel experience

Semantic differential for tunnel experience	No info	EU leaflet
unpleasant – pleasant	3,10	3,00
tight – wide	2,81	2,83
messy – tidy	2,40	2,28
dangerous – safe	3,19	3,44
mixed up – well arranged	3,43	3,33
stressing – relax	3,24	3,44
risky – safe	3,24	3,39
difficult – easy	3,57	4,17
scary – comforting	3,57	3,67
unreal – real	3,29	3,94

A T-test showed no significant group differences.

Subjective measures: Length estimations

The drivers were asked to make different types of estimations after each experimental condition. After the no-incident drive, drivers were asked to estimate the length of the tunnel. After the fire incident, they were asked to estimate how far into the tunnel the incident occurred.

A T-test indicated no significant difference between the groups in the estimation of tunnel length after first run or length to fire incident on second run.

The estimations were as follows:

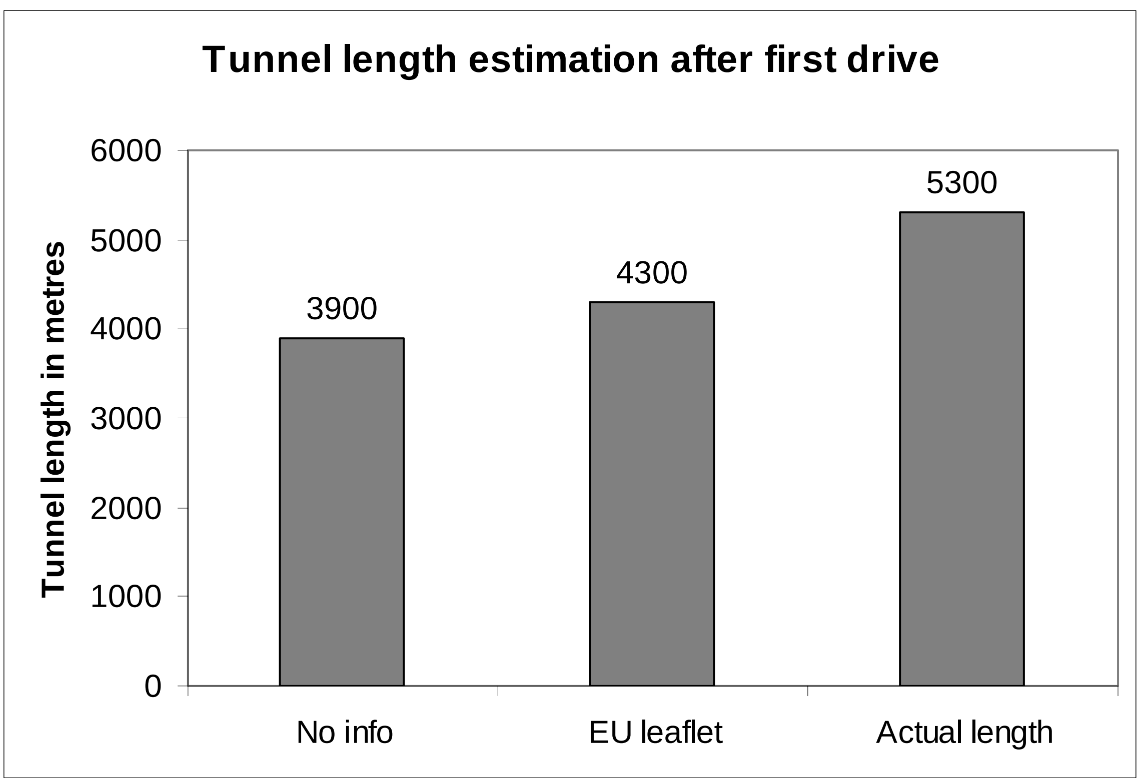


Figure 3.14: Tunnel length estimation

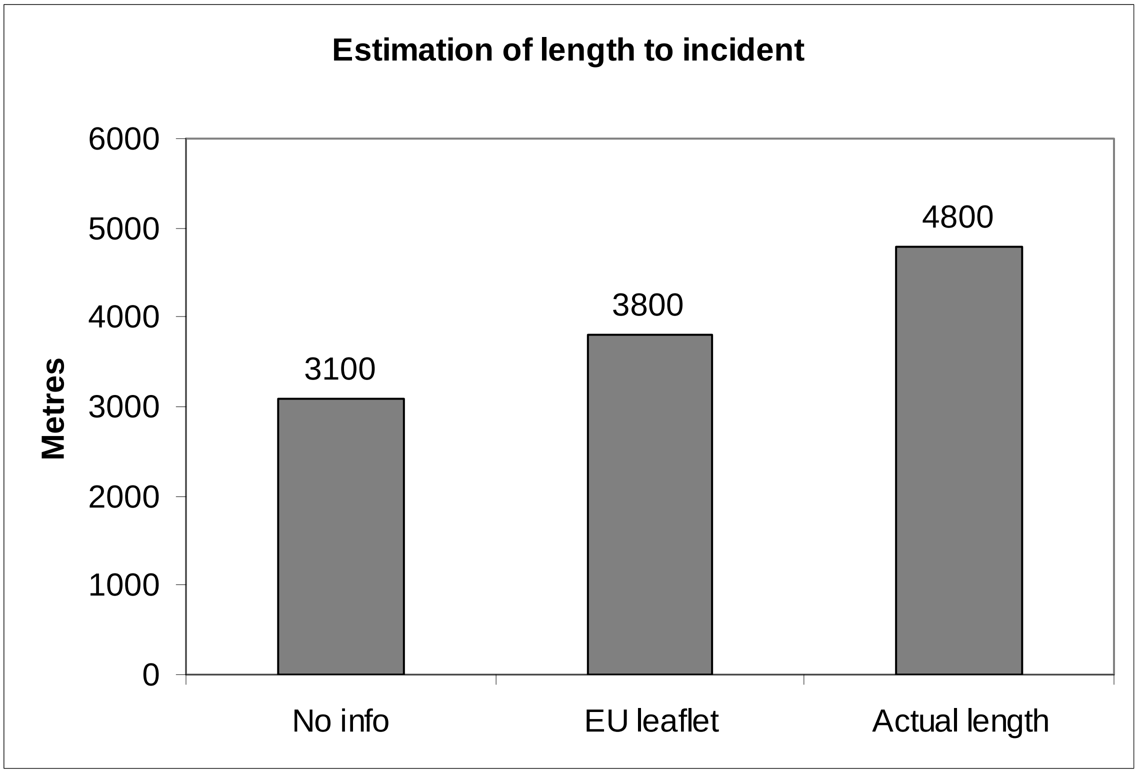


Figure 3.15: Estimation of length to fire incident

<u>Subjective Measures: Memory Items - Recall</u>

After the first drive with no incident, drivers were asked to recall any details of the tunnel interior. The answers were compared to a list of safety relevant features in the simulated tunnel. The bar chart below displays percentage of positive item recall without cues:

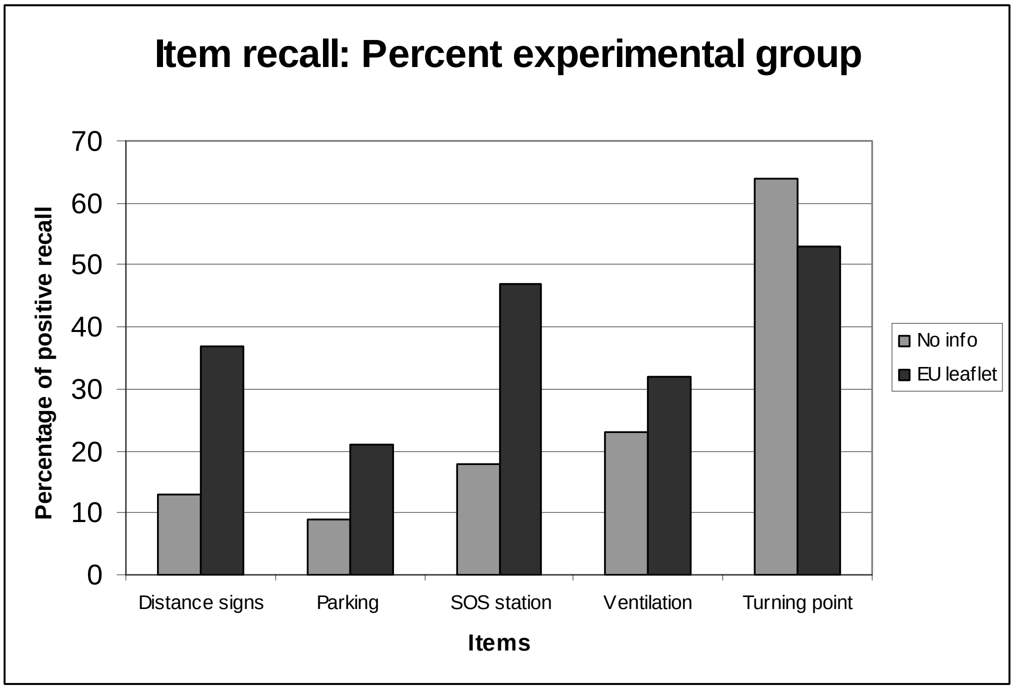


Figure 3.16: Percentage of experimental group on item recall after first drive with normal conditions

Table 3-36: Item recall - percentage of recall for each experimental group after first drive

	No info		EU leaflet	
	Recall	No recall	Recall	No recall
Distance signs	13 %	87 %	37 %	63 %
Parking	9 %	91 %	21 %	79 %
SOS station	18 %	82 %	47 %	53 %
Ventilation	23 %	77 %	32 %	68 %
Turning point	64 %	36 %	53 %	47 %

After the second drive, the drivers were again given a memory test, including item recall and item frequency. Results were as follows:

Table 3-37: Memory: Item recall and frequency after second drive

	No info	EU leaflet	Actual
Distance signs	3	3	4
Parking	1	1	5
SOS station	7	5	32
Ventilation	3	2	17
Turning point	1	1	2

Subjective measures: Simulator realism

After the experiment was completed all subjects were asked to rate several aspects of simulator realism. The bar chart below displays ratings of simulator realism on a seven point scale where zero indicates a negative experience of realism (unrealistic) and seven a very positive simulator realism for the specific item:

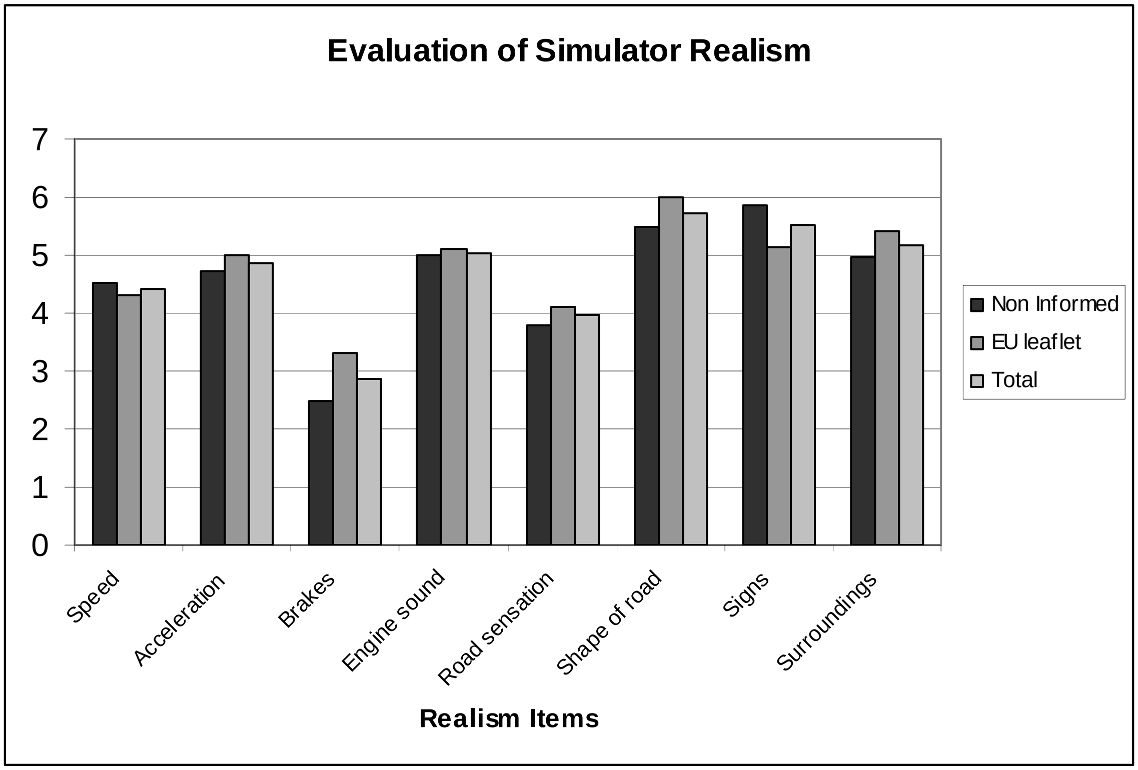


Figure 3.17: Overview of evaluation of simulator realism (0 = non realistic, 7 = very realistic)

3.2.3 Discussion

The objective variables from the simulator log file indicate the vehicle handling during the tunnel drive in detail. The variables cover aspect of driving as speed, placement of the truck, pedal use, and steering wheel movement. Analyses were performed in relation to the specific segments of the UPTUN driving simulator scenario.

<u>Objective measures in segments</u>

Results indicated few clear cut differences between the groups.

In segment 1, marking the first part of the tunnel, no difference was found. Speed and lateral position were approximately the same for the groups. One might have expected a change in behaviour due to the leaflet because it focuses on safety details that may prime safety relevant behavioural patterns. No clear pattern was seen beyond the statistical tests, neither between the groups nor across experimental conditions. The groups behaved very much alike in both trials in segment 1.

Segment 2 offered some tendencies of statistical significance, in which the group familiarized with the EU leaflet had higher standard deviation of lateral position values when driving the fire condition. This would indicate that these drivers tended to swerve more in their lane. Yet, the data is somehow deceiving in that they refer to very small distances. The difference in question in segment 2, fire condition, is down to centimeters and millimeters. The tendency of statistical difference may therefore be considered as of low practical significance. Beyond the tendencies commented upon here, segment 2 offered no major differences in terms of the objective variables.

Segment 3 marked the latter part of the descent from tunnel entrance down to the sub sea level. This segment offered a marked difference in mean speed in the first drive with normal conditions. The group with no info had higher mean speed than the EU leaflet group (61 km/h versus 51 km/h), yet, this difference was not statistically significant .The practical implications of the two speeds may be of relevance when outlining forthcoming human factor simulations. Another interesting finding is that the difference in speed in the first drive (normal condition) is diminished in the second drive (fire incident). It seems that the group with no info slows down, and the EU leaflet group replicates their speed level from the first drive. One possible explanation is that after the first drive, questionnaires concerning safety were given, as the memory item task. This may have triggered a more clear focus on safety for the group not primed by the EU leaflet. Concerning the remaining variables in segment 3, the distributions were approximately equal between the groups in both conditions. Other than speed levels, variables elaborating on the vehicle handling indicated no marked difference.

Segment 4 offered no major difference between the groups in either condition. Again, the higher mean speed for the no info group is also seen in the first drive through segment 4, and this difference is also diminished in the second drive. The remaining variables are in line with the patterns seen in the previous segments, in which few or no marked differences are seen.

Segment 5 marks the first steps of the accent towards tunnel exit. In the fire incident condition, the first signs of fire may be perceived here in terms of a light veil of smoke. In the first drive (normal condition); there is few or no difference in driver behavior as measured by objective variables. The pattern of driver data is approximately equal. In the second drive, the EU leaflet group shows tendencies of elevated standard deviation of speed. It is uncertain what to attribute this tendency to, but one possible explanation may be that the EU leaflet group responds to the first signs of something not being normal – at this point, the fire incident is a little more than one kilometer away.

Segment 6 marks the part of the tunnel in which the fire incident is located. The results focus on the driver behavior in relation to this, as the data is selected to represent only the last 1000 meters before the fire incident. The EU leaflet group drives slower and approaches the accident approximately with 3-4 kilometers lower speed, yet, the difference is not statistically significant. The variance of speed is equal, about 17 km/h. The other variables do not show any marked difference.

Minimum distance and observed behaviour

The distance from the interactive vehicle to the fire incident was measured. The EU leaflet group stopped four meters further from the fire than the no info group (16 meters versus 20 meters). This difference was not significant by statistical criteria, still regarding the mean values and the possible scenarios considering the standard deviation (8 meters for no info group and 15 meters for the EU leaflet group), practical values can be evaluated qualitatively. Combining the mean values with deviation, one may have a situation were a driver not primed on safety may stop the vehicle 5 to 8 meters from the fire, whereas the safety primed driver stops 30 to 35 meters away.

In addition to minimum distances, the dataset contained logging of behavior when drivers were confronted with the fire incident. The results show that 40 % of all the drivers stopped before the incident, and over 30 % stopped beside the accident. For truck drivers backing up or turning round is seldom an option in tunnels due to the size and length of the vehicle. Backing up in this study was chosen by only one professional truck driver in order to increase distance to the fire incident. This was possible since no traffic had yet cued up behind the truck. The content of the cargo may also influence behavior. Especially in terms of stopping distance to the fire incident when the driver is aware of the risk the cargo implies. It must be noted that the only information about cargo given prior to trials was that they were carrying a load of 50 ton. No indications of hazardous goods on board were given to drivers. It must also be noted that the tunnel cross section was large enough to allow a truck to pass the burning vehicles at the site of the fire incident.

Looking into the group difference shows rather few differences. The only marked difference would be that a larger part of the no info group passed the fire incident, and that 5 % of the EU leaflet group drove into the vehicles on fire, unable to regulate their distance. The behavioral descriptions may be seen in relation to the group values indicating that among truck drivers who stop before the incident, the EU leaflet group stops further from the incident. Yet, the variations over these mean values are informative and must be considered when understanding the results.

Workload - NASA RTLX

The NASA RLTX measures were administered after debriefing, test drive and after each experimental condition. NASA Retrospective Task Load Index measures 6 aspects of subjective workload; mental, physical, time pressure, performance, effort and frustration.
The workload measures yielded no significant differences between the groups in either condition or on any of the items. It seems that safety oriented information does not affect the workload demands in this simulator trial. One possible solution is that the drivers are more or less evenly competent in their driver skills, and that the simulator drive with the adhering situations does not affect their experience if the driving itself.

Subjective measures: Risk Perception

The risk perception schema was administered after the second drive with the fire incident occurring. The risk items tap into several aspects of risk perception; the probability, emotional component, rational assessment.

T-tests showed that differences in scores between groups were not significant. It seems that drivers no not regard tunnel risk differently after receiving the EU leaflet in this study. Yet, the scores show some systematic difference, though not significant. Drivers with the EU leaflet presented scores higher on the two items probing the subjective experience of the probability of self or others being involved in a tunnel accident. On the remaining items, they score lower than driver with no info. A possible interpretation of this might be that the drivers with the EU leaflet presented experience the probability as higher, giving rise to higher attention towards the matter, yet, the handling of an eventual incident is not regarded as frightening (emotional) or complex (what to do).

Subjective measures: Semantic scales

The two semantic scales aimed to assess experiential attributions after the tunnel drive. Comparison of the two group indicated that differences was not statistically significant. Beyond that, few systematic differences were seen, giving the impression that the scores were randomly distributed between the two groups. The semantic scales may thus be indication of an overall experience of tunnels, founded in driver's real life experiences of tunnels and independent of any additional information first in this experiment. The simulator experience may not be sufficiently ecologically valid in order to give to real sensation of danger.

Tunnel length estimations

After first drive, drivers were asked to estimate the length of the tunnel. Further, following the second drive, the subjects were asked to estimate how far into the tunnel the accident occurred. The T-test showed no significant difference in group mean values in estimation. Yet, on both occasions, the drivers with the EU leaflet presented were closer to the actual lengths. Regarding the actual length, group 1 (no info) was approximately 1400 meters off mark, whereas group 2 (EU leaflet) were 1000 meters off. In terms of length to incident, group 1 was 1700 meters off, group 2 fell short by 1000 meters.

These results have some value in term of relative difference between the groups, where the fact that drivers with no info seem to underestimate length might be crucial information in case of a tunnel fire (but there is no difference between groups, so there is a general underestimation of length). Yet, the estimations are probably heavily affected by the fact that this is a simulator trial. An interesting follow in actual tunnels would be to investigate whether this group difference still holds in ecological valid surroundings.

Memory Items

The memory items look into how much safety details the drivers recalled from their drive. After the first drive, they were given the task of mentioning details they remembered. A larger percentage of the EU leaflet group recalled such details as the percentage in the no info group, such as distance to exit signs, turning points, SOS stations, and ventilation fans. Yet, fewer of the EU leaflet group recalled the larger turning points compared to the no info group. The results were not statistical significant, but may be considered of practical value in the sense that recalling fewer turning points, SOS stations and other safety relevant interior may affect the perception and experience of the environment when crisis occurs.

After the second drive, the participants were asked to recall details and specify how many of the objects they saw. Common to both groups is that they underestimated the frequency, especially ventilation and SOS stations. Otherwise both groups seemed to have similar estimation of the other safety details.

Realism of the simulated tunnel

After the second drive all drivers were asked to evaluate the realism of simulated tunnel on a scale from 0-7 were 0 equal unrealistic and 7 equals very realistic. The results show that the realism items *shape of road*, *signs*, *surroundings*, *engine sound* and *acceleration* all receive a fairly high rating (5-6).

The realism item *brakes* receive the lowest rating (2-3) indicating an unrealistic sensation of braking forces when brakes in the truck are activated. Comments from the truck drivers during the trial indicate that this was especially pronounced when applying brakes downhill in the simulated sub sea tunnel. The latter is to be expected since the truck simulator only has vertical motion in the seat. No G-forces are induced in the simulation. However acceleration receives a fairly high rating and should be expected to be subject to the same lack of G-forces as for braking. The rapid change in peripheral visual cues, when accelerating from zero to speed limit (80 km/h) or above are however, more pronounced than during the change from high speeds to a low speeds.

A validation study the simulator is being prepared (PhD study to be finished in June 2005) yet at present we do not know to what extent the truck driving behavior in the virtual model of an existing tunnel holds in ecological valid surroundings. Neither do we know the ecological validity of the fire incident. However, prior to the experiment 5 professional fire fighters were invited to drive in the simulator and to stop by the simulated fire incident in order to give a subjective evaluation of the fire incident.

The expert evaluation from fire fighters, who all had experienced real or realistic fire training sessions/incidents in road tunnels, indicated that the simulation of the fire incident in the present study is realistic in terms of fire dynamics and visualization. The visualization was made with reference to video footage of real tunnel fires with truck involved. Critical remarks from the expert group were related to the color of the increasingly dense smoke on the approach to the fire. This should according to the experts have been darker, although they had a discussion about fire stage and type of material on fire. Indicating some tunnel fires with certain materials may in an early stage produce white smoke. Burning tires, as visualized in the experimental fire incident would produce dark smoke (as can be seen in Figure 3.5). No corrections of smoke colors were made prior to the experiment.

Another critical remark was related to the smell of smoke. No smell of smoke was present during the experimental trials reported here. The possibility of inserting real non toxic smoke (the smelly type used for training purposes) and the theatrical non-smelling type was considered prior to the experiment to enhance realism. Smoke was however not inserted in the truck cabin or outside during the experimental trials due to cost and time constraints. It would take considerable time to clear the air between subjects with the current ventilation system in the simulator.

3.2.4 Conclusion

The Sintef UPTUN simulator trials were initiated in order to outline behavior of tunnel users and the factors that will initiate this behavior (GRD1-201 / version 24 July 2002: p.54). The tunnel users in focus here are skilled truck drivers and their response to the priming of safety issues as exemplified by the EU tunnel safety leaflet. Their behavior is described in terms of objective variables from the simulator log file, specifying quite rigorously the speed, lateral position, steering wheel movement, pedal use, and so forth. Further, qualitative descriptions of behavior are collected in close contact to the fire incident. Other subjective measures were also added; mental workload, risk assessment, and memory for safety details. The drivers first drove under normal conditions with no incident, then with a fire incident occurring inside the tunnel.

Overall, the driver behavior showed few or none major group differences. Yet, some patterns concerning speed and minimum distance from parked vehicle and fire gives some indications of how tunnel users might behave. The experimental condition in the study is the introduction of EU leaflet to one driver group. This may be considered as a small intervention in terms of priming of safety issues. The differences found, both statistical significant and of practical value, are not expected to be robust. There are no assumptions of long term change or transfer value to real driving. The explanation for the big number of crashes may be due to the combination of too high speed and poor visibility. In addition the behavior in real life may be different compared to a simulated environment due to different perceived risk. The study rather outlines exemplification of a safety approach putting weight on increasing the awareness of relevant dangers and functional behaviors associated. A follow up study could go further in investigating the extent of safety material used, for example using leaflet supplemented by a video giving more precise visualizations and instruction of correct tunnel behavior. The project should consider not only what type of information to be presented, but also the extent and integration for instance as a part of drivers education.

The UPTUN research programme investigates features relevant for increasing safety in existing tunnels. This current study has focused on the behavior of the truck driver and the priming of safety knowledge prior to confronting a tunnel fire incident. From a psychological perspective, there are various types of information that may be useful to consider separately. The importance of this information and how time critical it is depends of the situation On one hand, there is the immediate, context-dependent information given during the incident (messages over speaker, specific orders of where to evacuate in the specific tunnel in question). This is the immediate information. On the other hand, there is the acquisition of safety relevant knowledge, as general rules of what one usually should do, various safety heuristics (“rules of thumb”) valid for most situations. This type of knowledge is a more elaborate cluster of specific mental models and attitudes towards safety.

The two types of knowledge differ in time span and context relevance (“here and now” and specific situation versus long term and general advice). The future effort of safety work must elaborate on the coupling of these two types of knowledge, ensuring that drivers have a proper general knowledge of what to do in case of tunnel fires, and on the other hand provide adaptive context-dependent information on site. The underlying psychology of this is to design tunnels and immediate information sources so that they can trigger already acquired general safety knowledge. The goal is to be able to combine long-term knowledge with current information into adaptive, skilled human performance in high risk environments.

The data material may give rise to the aggregated description of behavior of the two experimental groups. Yet, the variation of group level data offers some insight into the various types of behaviors that might occur in tunnel fire incidents. Based on this information, different accident scenario concerning human factors may be described and tried out in accordance to forthcoming simulations. Especially mean speed values, headway to other vehicles and minimum distance to incident may be of interest, as well as descriptions of driver behavior once confronted with the accident.

These driving simulator tests focused on driving behaviour and the cognitive processes that take place after drivers discover a fire in a tunnel. After this phase, the next phase ought to be evacuation. The next series of studies focus on the tunnel user if evacuation starts.

4. EVACUATION STUDIES

L.C. Boer, J. Winer & A. Noren
TNO Human Factors, the Netherlands

Accidents in road or train tunnels endanger those directly involved in the accident. And once a fire breaks out, all who happen to be there are in serious danger, because smoke can disorient and suffocate people in the confined space of a tunnel.

Measures to prevent such tragedies are: technical measures such as one-directional traffic per tunnel tube, or public campaigns aimed at safer driving and being on the alert for fires. Despite all precaution, fire accidents cannot be prevented 100%. Therefore, measures are also useful that mitigate the consequences of fire accidents. Technical measures are: fire extinguishers or sprinklers in the tunnel, and escape ways enabling people to leave the disaster tube and walk to safety. Most tunnels do have such escape ways; but the question is: does the public know to find them in emergencies? And: how long does it take it to leave the tunnel?

This chapter presents data on the time needed for tunnel evacuation. With this information, BRE (Building Research Establishment, the UK's leading centre of expertise on building and construction and the prevention and control of fires) can update their evacuation model (the already described CRISP model). This update will be described in Chapter 6.

In the early moments of the accident, the fire will be small and the opportunities for escape are good. Later on, the fire may have grown and smoke may have obscured 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. It is also important to know what measures should reduce the time needed for evacuation.

The time needed for evacuation is *not* the same as the time needed to walk to the emergency exits. Accidents come by surprise, and the victims of a disaster need to abandon their original plans. That takes time. Hence, adequate models of evacuation should have a first stage called "awareness time" or "reaction time" before the public starts to walk to the emergency exits (see e.g. Passenier & Van Delft, 1995). And people may *hesitate* before they finally decide to leave. TNO therefore proposes three stages (reaction time, hesitation, and walking), based on observed behaviour.

The current chapter presents this three-stage model, and quantifies the duration of the stages based on observations in road and rail tunnel studies. The quantification addresses both the transition between consecutive stages as well as the distribution of the time required per stage. For road tunnels, a complete three-stage model of evacuation time is presented. For rail tunnels, a partial model is presented because observations on planned egress only were available. The chapter ends with an example of how the model can be applied and discusses computer modelling.

4.1 Stage models

4.1.1 Existing stage models

Understanding the individual's perspective during an emergency is of crucial importance for understanding evacuation in general. The human perspective goes through several stages from the moment that an accident occurs to the moment that the situation is safe or normal again..

Passenier and Van Delft (1995) divide the individual's perspective into four stages. The incident is processed in Stage 1, situation awareness. Motorists who perceive the situation as a congestion don't see the danger; and Stage 2, threat assessment, does not lead to an alarm reaction. Signs of danger can come from the incident itself or from public announcements. In the latter case, they are direct input to Stage 2. Once the threat assessment is beyond a certain threshold, motorists are alarmed and will look for refuge. Stage 3, Decision Making, is concerned with preparing the flight. Personal property is secured, clothing adjusted, and goodbye is said to the car. Directions of others can give direct inputs to Stage 3. Knowledge of escape ways are also inputs to Stage 3. Stage 4 is going to and through the escape exits, see Figure 4.1 for details.

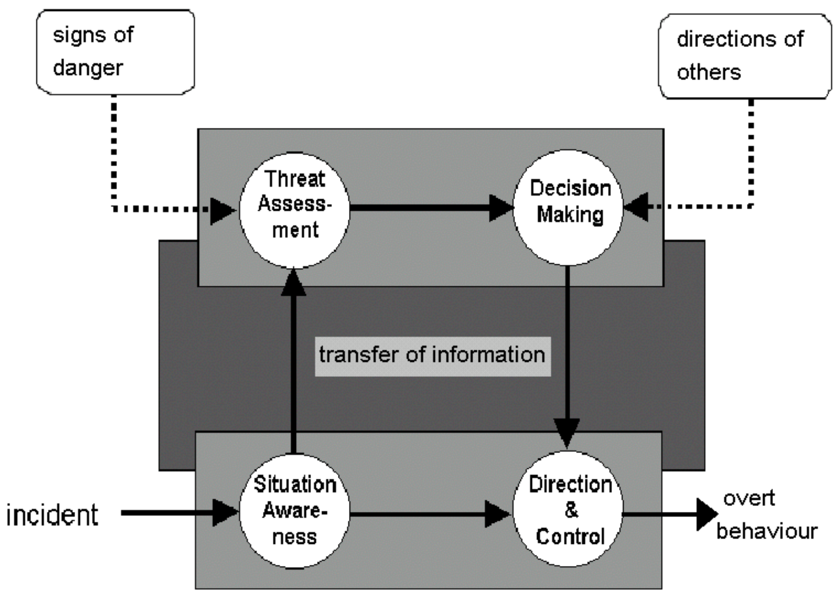


Figure 4.1: Four stages of information processing (Passenier & Van Delft, 1995)

The four stages can overlap in time. 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 the car, back to Stage 3. And some motorists can be in Stage 4 while others are still in Stage 1.

Canter (1985) divides the human perspective during emergencies into five stages.

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 by 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.

Recently, Canter (1990) divided 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) created a model for stress behaviour during fire emergencies. The model consists of loops, where the initial loop deals with the ambiguous information of early cues. Depending on how a person evaluates the information, other loops follow. The decision-making becomes harder the greater the uncertainty. Early and precise information reduce uncertainty and confusion, and enhance the decision-making process. The psychological stress of the person is modified by three factors (Idzikowski & Baddely, 1993). The first factor is the person's predisposition to stress. Everyone has a trait-anxiety that is relatively constant during a person's lifetime, and a state-anxiety that depends on the situation. Both can influence performance. The second factor is the subjective perspective. 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.

Other models are developed by Bickman, Canter, Sime and Proulx; in many cases the result of decades of research. Either the models are based on different perspectives 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.

4.1.2 Model of the current report

The stage models mentioned earlier are more or less similar, starting with lack of information, uncertainty, and ambiguity; etc. We will use a simple model that helps to classify data from video recordings. Our model is based on observable behaviour.

Behaviours that can be observed are: (a) stepping out of the car, (b) hanging around the car, and (c) walking towards an emergency exit. The period between leaving the car and walking towards the exit, we call "hesitation". This defines three stages: (a) waiting in the car, (b) hesitation (the time between opening the door and the moment the motorist begins walking) and (c) actual walk towards the exit – see Figure 4.2.

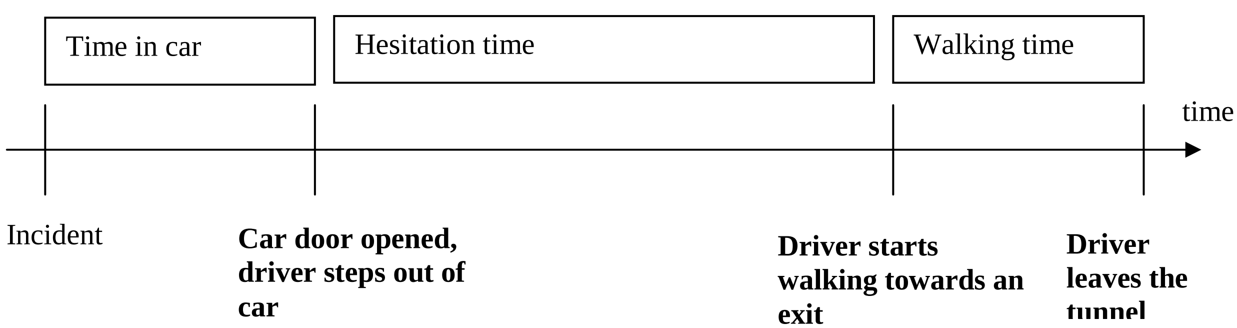


Figure 4.2: The current model.

The three stages are easy to quantify and correspond to the four stages of Passenier and Van Delft. The starting point is how an observer sees the train of events. In contrast, Passenier's model does not enable us to observe the stages from video recordings. Situation Awareness, Threat Assessment and Decision Making can all take place while waiting in the car or during hesitation. Hence, it is impossible to determine when any stage starts or ends.

In the following sections, we will fill the model of Figure 4.2 data with observations from evacuation of a road tunnel after a (staged) heavy goods vehicle on fire.

4.2 Road tunnel data

Observations of road tunnel tests are used to fill in the model of Figure 4.2. For economy of quantification, we will use cumulative density distributions. These distributions describe a specific stage such as Leaving the Car with a few parameters such as mean time and standard deviation. Combination of the distributions of different stages makes it possible to draw conclusions about the total evacuation process.

4.2.1 Method

Unannounced evacuation tests were carried out in January 2002 with the following scenario (Boer, 2002; 2003). A heavy goods vehicle (HGV) was driving slowly on the left (fast) lane of the tunnel, its alarm lights blinking. The test participants (who drove their own cars) reduced speed and remained behind the HGV. Halfway down the tunnel, smoke started to develop and the HGV stopped across the roadway, blocking both driving lanes (see Figure 4.3).

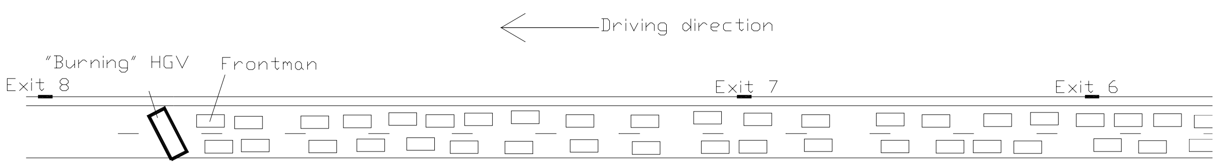


Figure 4.3: Test settings in the nine tests. (The tunnel is 1 km long and 10 m across. Distance between Exits 8 and 7 is 100 m; between 7 and 6 is 50 m;

Approximately five minutes after the HGV stopped an announcement was made via the loudspeakers in the tunnel, “Attention, attention, there is an explosion hazard; I repeat, there is an explosion hazard”. After two more minutes another announcement was made "please leave the tunnel; please leave the tunnel".

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 test runs would take place later. Therefore they did not expect an incident or an evacuation.

There were 7 replications of the study, all of them with the same scenario, all of them with two public announcements. Two more tests were made for control purposes (Test 8 and 9). This time; the participants were told in advance about the HGV and that they should find refuge as soon as the HGV came to a halt. No announcements were made.

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 motorist’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 motorists. Figure 4.4 shows the four camera angles and Figure 4.5 shows the HGV with two lanes of stopped cars behind it.

Figure 4.4: The four camera views.

Figure 4.5: Stopped cars behind the burning vehicle.

Analysis plan

The basis of the analysis was the videotapes. The camera views were limited, and sometimes the back of the congestion was out of view, especially when in Test 4 all motorists took the left lane resulting in a very long queue. The result is a reduction in the number of participants that were used for the analysis. Table 4-1 gives an overview.

Table 4-1: Number of participants observed in the evacuation tests of the road tunnel.

Test number	
unexpected	
1	31
2	32
3	26
4	10
5	28
6	30
7	36
Advance information	
8	35
9	34

For Stages 1 and 2, the data of Test 1-7 were used, unannounced evacuation. For Stage 3, all data were used (including Test 8 and 9 where the participants had advance information about the purpose of the study).

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.

4.2.2 Results

By performing different evacuation tests, evacuation models can be updated. Since a lot of variables influence behaviour and not everyone behaves in the exact same way, models never correspond one to one to reality. However, if we keep on improving the models with real life data, the models will be able to help us predict situations we have not yet encountered yet.

Stage 1, leaving the car

The first stage is the time before people open the door and step out of their car. Even though this stage was also part of the driving simulator stages, there needed to be some overlap. In the driving simulator studies, the idea was to see if there was a difference in cognitive processes and understanding the situation. Since the studies were situated in a driving simulator people probably had the awareness that it might not be the right thing to do to get out of the car. Therefore, measuring the times it took people to really get out of the car in the simulator studies would not be an appropriate measure, since most people claimed to leave their vehicle but did not actually do so.

Measuring that process here (in a more realistic situation) is therefore very useful. For practical purposes, we divided the population into two parts: those leaving the car spontaneously, on their own initiative; and those leaving their car at the (first) announcement. Observations of 3 participants were ignored because they reacted *during* the announcement; it is difficult to say whether they acted on their own initiative or were very fast to react to the announcement.

Before announcement

Summed over the seven tests a total of 35 participants left their car before the announcement. That is 18% of the population (N= 193 - 3, because 3 participants were ignored in this analysis). The cumulative distribution over time reveals two subgroups (see Figure 4.6). The first group consists of 18 persons reacting during the first minute already; the second group consists of 17 persons beginning to reacts after 2½ minute. A significant change in the distribution between 80 and 130 seconds is evident.

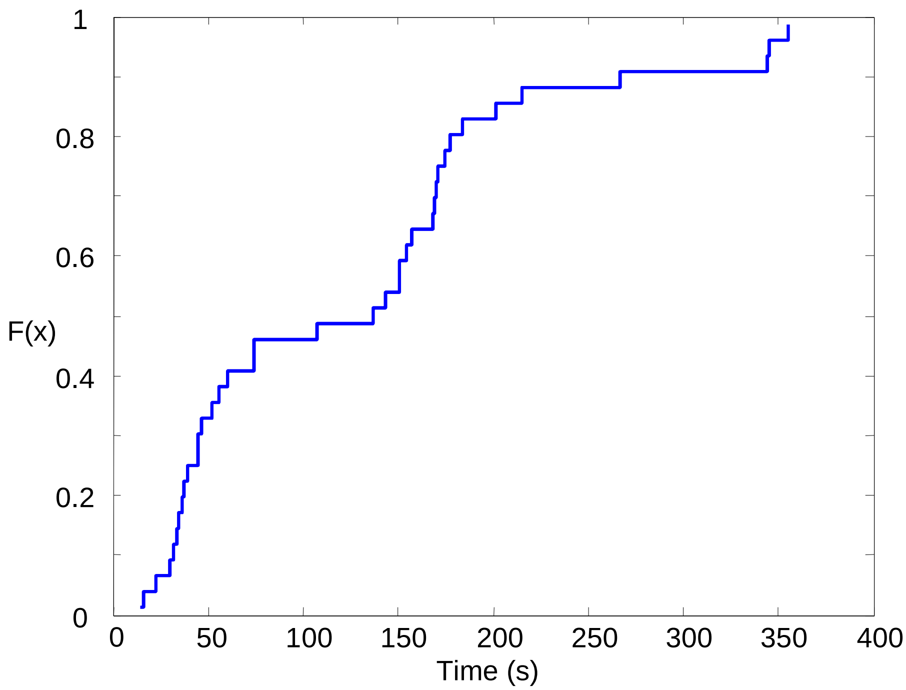


Figure 4.6: Motorists (18%) reacting spontaneously, before the announcement. Two subgroups are apparent: the first reacting during the first minute; the second waiting for 2 minutes at least.

The statistical description of motorists reacting spontaneously before the announcement is:

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

(the first and second function are for Group 1 and Group 2, respectively). In the following figures the “Before announcement” subgroups are shown separately. Red curves indicate the fitted statistical approximation.

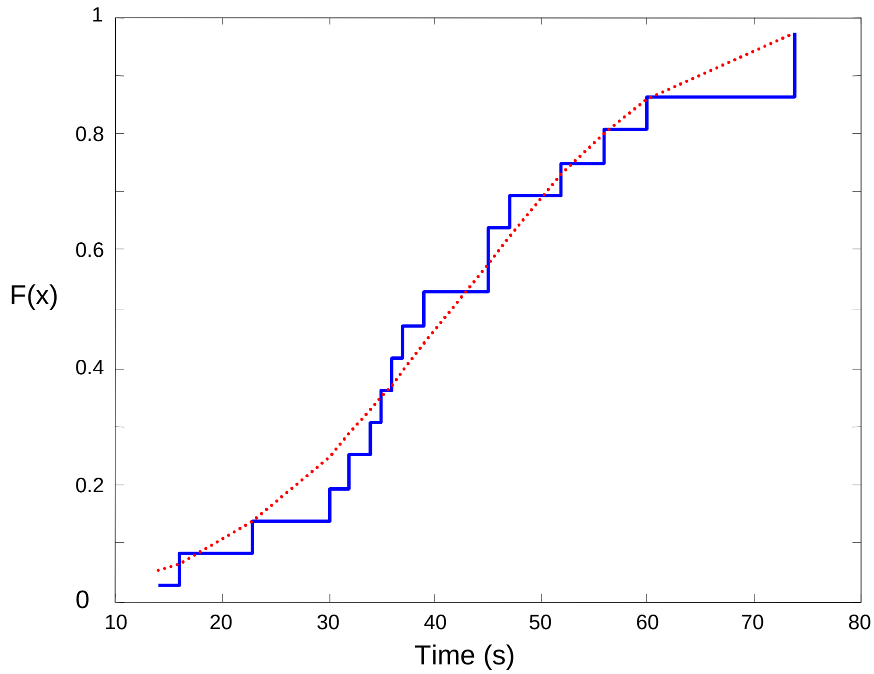


Figure 4.7: The data from the tests, "spontaneous action", and the approximated statistical distribution for Group 1 (early reaction, Norm (41.6; 17.1)).

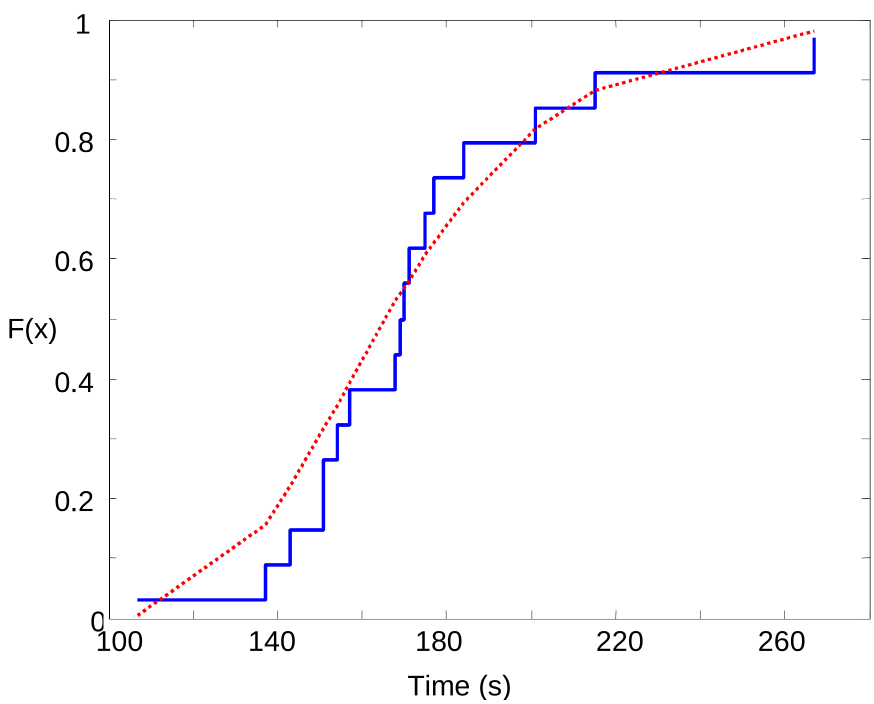


Figure 4.8: The data from the tests, "spontaneous action", and the approximated statistical distribution for Group 2 (late reaction, Gumbel (28.8; 155)).

After announcement
Most people, 155, began to react after the announcement of the operator. That is 82% of the population (N= 190). The data are shown in Figure 4.9, where t=0 represents the moment of the announcement (about 330 s after the stop of the truck). The figure also shows the best-fitting distribution: a Generalised Extreme Value (GEV) distribution:

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

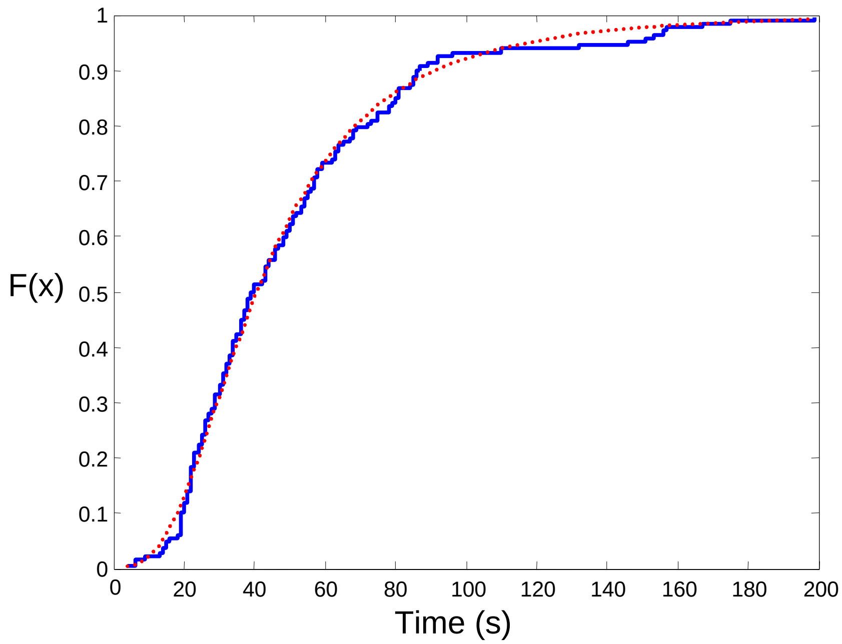


Figure 4.9: Motorists (82%) reacting after the announcement. The dotted line represents approximation by a Generalised Extreme Value distribution (-0.22; 19.91; 33.08).

Total population
Combined estimates of Stage 1, leaving the car, depend on the moment of the announcement. For the current tests, where the announcement came 330 s into the incident, the total process of leaving the car can be represented by:

X = (330+(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 Figure 4.10.

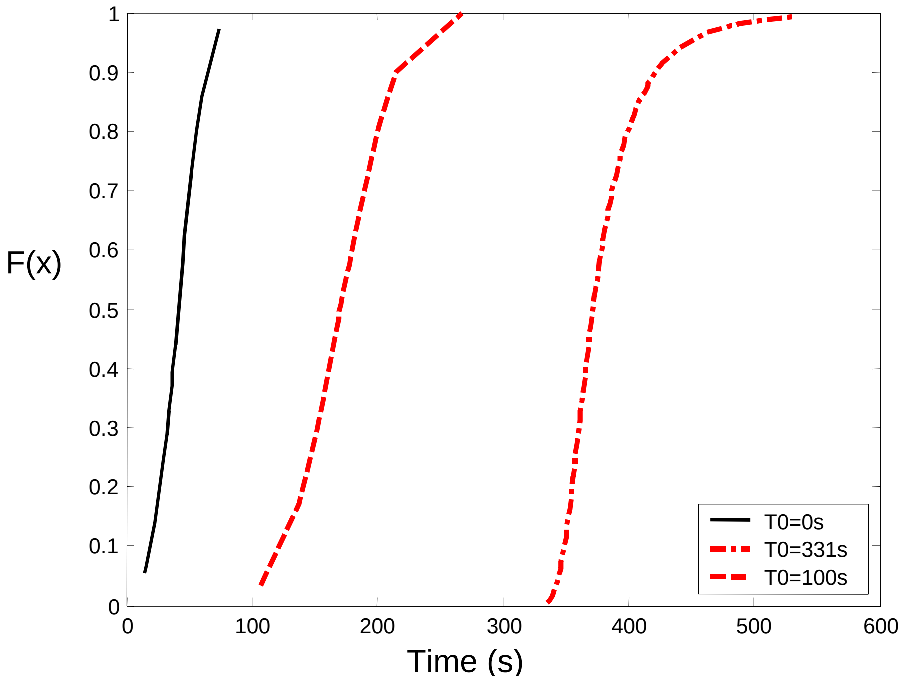


Figure 4.10: Stage 1, leaving the car, described with three distributions. (The first two curves represent 9% each of the total population; the last curve represents 82% and is, therefore, more typical.)

Stage 2, hesitation time

The second stage is the time lost hesitating standing on the roadway. A total of 46 motorists did not loose time--they went directly to an emergency exit after leaving the car. The others lost some time hesitating.

We maintain the distinction between those who had left their cars on their own initiative (Figure 4.11) and those who left their cars after the announcement only (Figure 4.12).

Visual inspection of the figures reveals that those reacting before the announcement hesitated much longer than those who reacted after the announcement. In the *before* group, hesitations longer than 100 s are observed 26 times (n=35-3; 3 left without hesitation), whereas the *after* group (n=155-43; 43 left without hesitation) has only one hesitation longer than 100 s.

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).

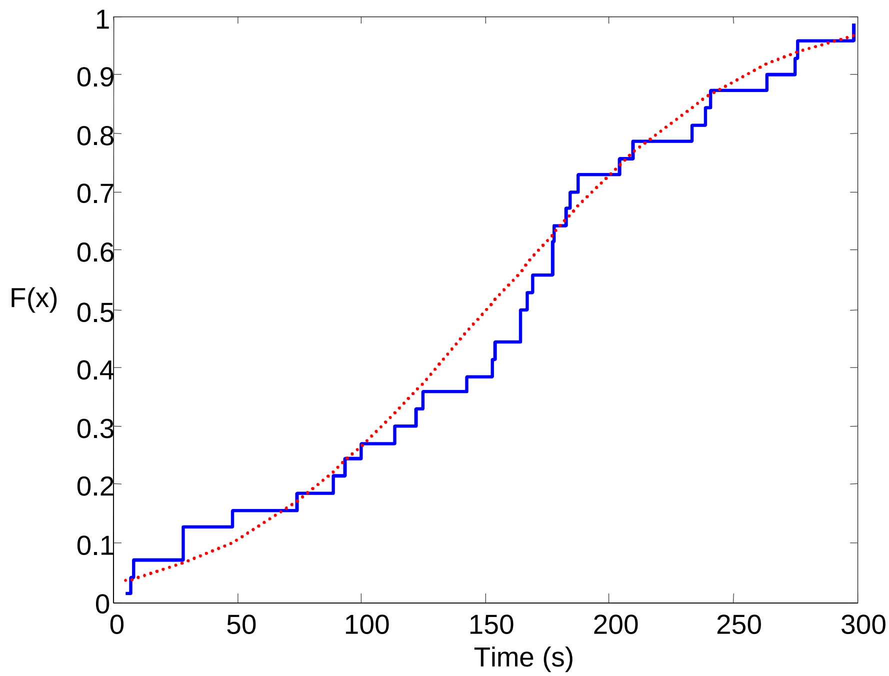


Figure 4.11: Time lost hesitating, actual and approximated distributions of motorists reacting spontaneously, before the announcement. The estimated distribution is Norm (151; 81)

The empirical and estimated distributions, the dotted line, are shown in Figure 4.11.

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 4.12.

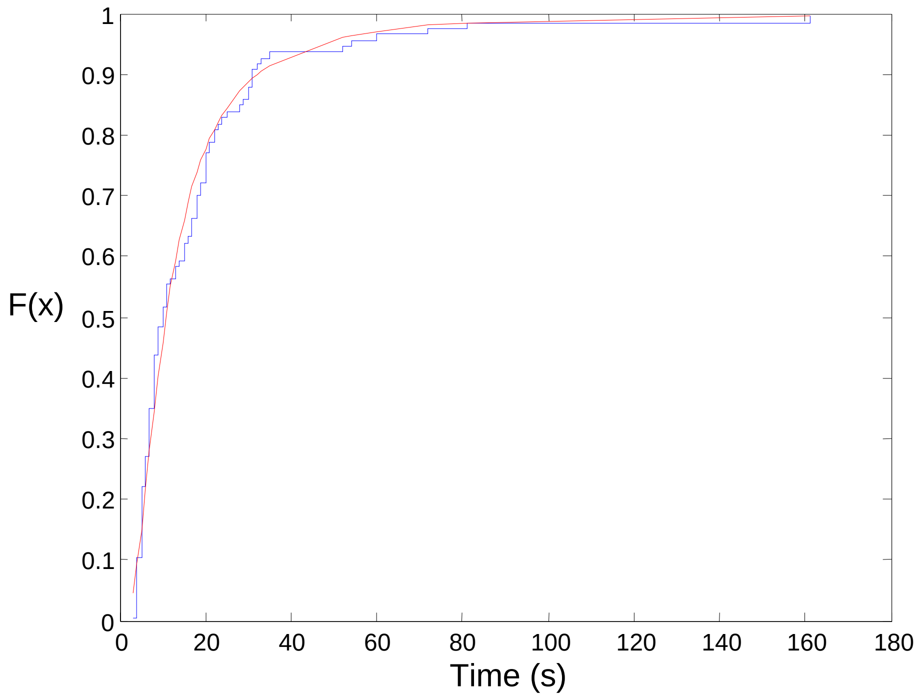


Figure 4.12: Time lost hesitating, actual and approximated distributions of motorists reacting after the announcement. The approximation is GEV (-0.54; 6.10; 8.31).

<u>Stage 3, walking</u>

The third and last stage is the time required to walk the distance to the emergency exit. No participants ever chose the exit beyond the HGV (Exit 8) even when it was the nearest exit. Only in the last two tests (evacuation announced and HGV not emitting smoke), 3 participants of 71 went past the HGV. The conclusion is that motorists will not pass a burning obstacle. Participants 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 motorists all walked in the driving direction. In short, 94% selected the nearest exit; the few selecting another exit always went forward.

In short, when can assume that the exit past the fire is, for all practical purposes, never selected; that 94% of the people will walk to the nearest exit; and that 6% will walk to an exit "up front" (into the driving direction) which is next nearest.

In order to derive the time spent in Stage 3, one needs to know *walking speed*. We therefore present the walking speed rather than the time needed for each individual. Walking speed is derived assuming two straight lines: one from the car to the wall, the other to the exit. The average walking speed was 1.33 m/s with a standard deviation of 0.55 m/s; Table 4-2 shows the data of the individual tests.

Table 4-2: Mean walking speed and standard deviation for 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

In Test 9 the area in front of one emergency exit became quite crowded and many participants had to wait.

We base our estimate of walking speed on Tests 1-7 that are closest to reality. The best-fitting distribution is the Gumbel distribution shown in Figure 4.13: Gumb (0.4431; 1.1185) m/s

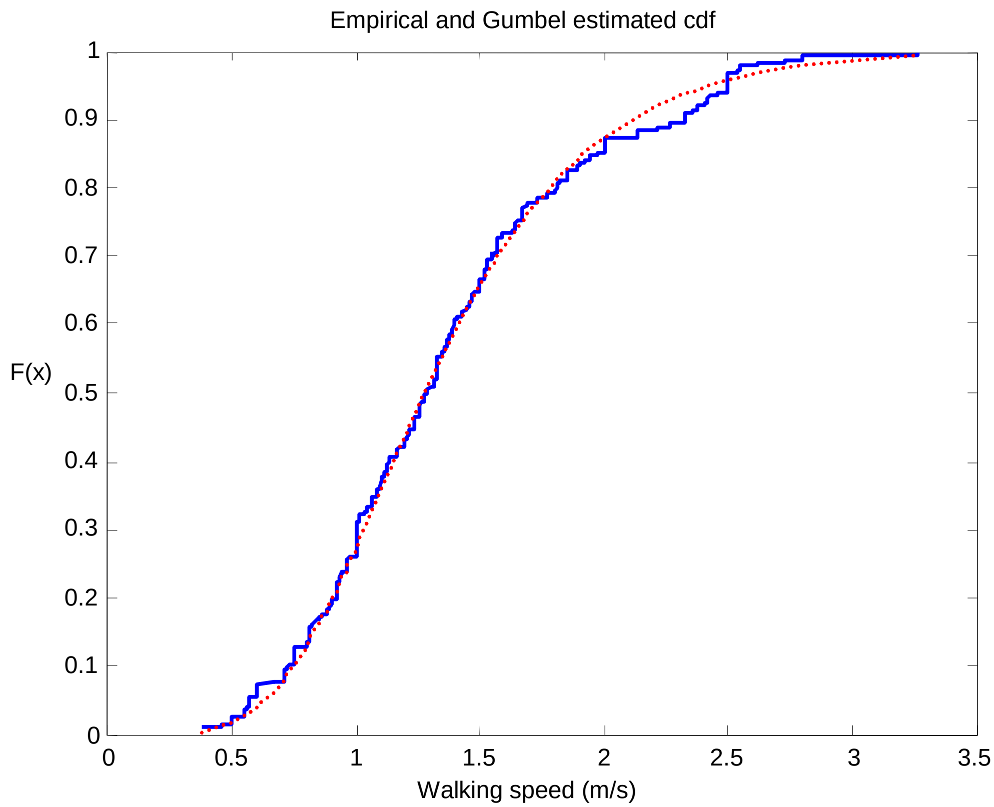


Figure 4.13: Walking speed in the Tests 1-7 and the estimated Gumbel distribution (0.4431; 1.1185, fitting 85% of the population).

The tunnel's lowest point was between Exits 6 and 7. Motorists walking from that position went uphill The gradient of the slope is 4½% in the tunnel. Other motorists went downhill 4½% , for example, those who stopped between the HGV and Exit 7, and returned to Exit 7. A check was made to see whether there is any difference in walking speed.

Table 4-3 shows the motorists walking uphill and downhill in every test. In Test 1 for example, Motorists 1-8 in the left lane stopped between Door 7 and the HGV and Motorist 16 in the left lane stopped between Doors 5 and 6. These motorists walked downhill. Motorists 9-15 in the right lane stopped between Doors 6 and 7 and walked uphill etc.

Table 4-3: 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 4-4.

Table 4-4: 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

There was hardly a difference between walking uphill and downhill; and the "difference" we observed was that uphill was "faster". The conclusion is that a tunnel slope of 4.5 % does not affect the walking speed when people evacuate.

Herd effects

For leaving the car, Stage 1, group behaviour is apparent when the data of all 7 tests are combined, Figure 4.14, every test represented by one curve. At visual inspection, most curves have similar steepness but quite different starting points. An elegant explanation is the "herd" effect: where one sheep goes, another follows; or copying the initiative of others.

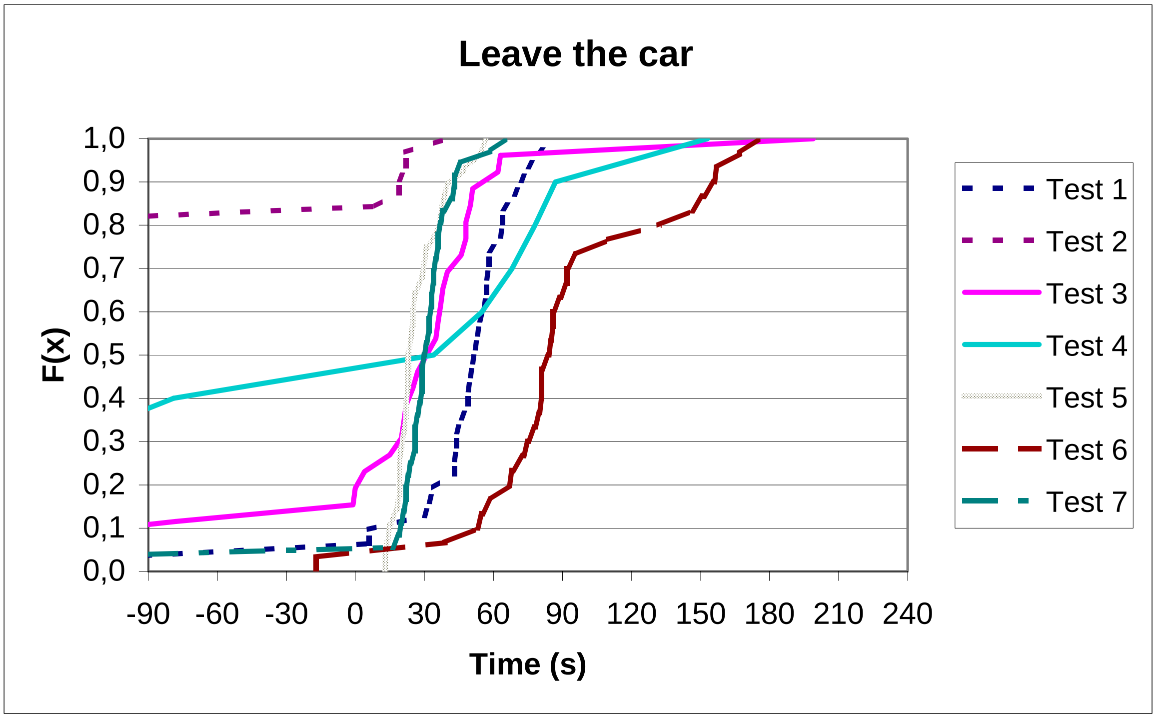


Figure 4.14: Cumulative frequencies of people leaving the car (the announcement "explosion danger" comes at T_O).

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 4.15: Motorists copying one another's behaviour.

When it comes to leaving the tunnel, group behaviour is even more conspicuous. In four of the tests almost all the people left the tunnel within 60 seconds, see Figure 4.16.

Figure 4.16: 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).

Reaction to different announcements

Two announcements were made. The first, issued 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 most tests, the tunnel was already deserted when the second announcement came, but in Test 6, there were still people present during the second announcement. Perhaps they failed to hear the first announcement. We refrain from drawing any conclusion about the effect of the second announcement. Considering that the first announcement was already effective, the addition "via the emergency exits" is probably not required.

Other behaviour

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), probably because of herd effects. This behaviour illustrates the concern about how to leave the car. In real emergencies, instructing motorists how to leave the car could save valuable time.

There are several behaviours in the tunnel that could be the focus for studies in the future. Examples are how motorists leave their car, why some motorists walk around in the tunnel rather aimlessly before deciding to evacuate.

4.2.3 Discussion

Are the data of the road tunnel studies valid? Validity is in part a question of the reality of the stage model. Does the human behaviour work like we have presumed when dividing it into stages 1-3 above; that is, 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 comes from analyses of real accidents. Both the Tauern and Mont Blanc tunnel fires (see Section 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 too long. Lacking confirmation that there is a real danger, motorists tend not to act at all.

These accident analyses lend support to our notion that the victims of a disaster go through a number of stages with the first stage characterised by a feeling of false security, and people continuing with whatever they were doing before the accident. Once aware that there is some actual danger, they investigate it but they will evacuate only when they get some sort of confirmation of the danger. We conclude that our stage model could be valid.

Are the data of the road tunnel studies also reliable? A satisfactory reliability means that repeating the studies elsewhere should provide the same result. Part of the question is the number and the selection of test participants.

The 9 nine tests involved 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 road tunnel users (see Appendix 4).

The statistics presented in section 3.2 show that the number of participants is sufficient for good reliability in all conclusions.

Hence, the purpose of this section, determination of the time spent in the different stages between occurrence of the accident until the moment that all people in the tunnel are safe, is achieved with validity and reliability.

4.2.4 Conclusions

Summaries are presented about the different times as well as their distribution.

<u>Group behaviour</u>

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 (Group 1) and after the announcement (Group 2) is made. The group that reacts before the announcement is discernible into two more populations, one that reacts early (Subgroup 1A) and one that reacts later (Subgroup 1B).

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.

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 may miss the announcement because they listen to the radio. If they see others getting out, they will understand that something has happened and realise that they too ought to react too.

<u>Time to leave car</u>

There are three populations; two reacting spontaneously before any announcement is made and one reacting after an announcement only. Most people belong to the last population.

Conclusions can, however, only be made about the distribution within the different groups since the distribution of people between different groups depends on the time of the announcement. 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)))

More tests are required to be able to draw conclusions on how the distribution between the different groups is affected by the time of the announcement. 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.

A somewhat philosophical point is who will help the operator. The operator is human, and subject to similar processes as the people in the tunnel. He, too, may loose valuable time because there is no-one announcing to him that the situation is dangerous.

<u>Hesitation time</u>

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.

Walking speed

There are 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 are similar to our results.

No difference downhill or uphill

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

Which exit

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

- People do not walk beyond a vehicle on fire.
- 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.

4.3 Train tests

Less data were available for evacuation of trains in tunnels. There were two planned evacuation exercises, one in Best and another in Stockholm. These recordings will be denoted as "exercises". Planned, that is, the participants were informed in advance what was going to happen. The evacuation never came as a surprise and there was no uncertainty about whether to leave the train, etc. Boer, Winer and Noren (2004) collected supplementary material for different train stations with passengers alighting under normal conditions from trains (no exercise). Together, this comprises the data set. The data give information about 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. It is clear that the full stage model of tunnel evacuation cannot be applied to these data.

4.3.1 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 exercise executed in 1999 and reported earlier by Frantzich (2000) and a normal observation of alighting passengers. A total of 978 people were observed exiting trains.

The 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.
- Specific flow was calculated which is the flow per metre door width (see Interim guidelines, 1999).

We will now describe the 6 different stations and their data. After a summary table, an analysis is presented on the effects of (a) door width, (b) vertical distance to the platform, and (c) luggage carrying.

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 on a Wednesday in 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 4-5. To reach the platform, passengers had to go down a few steps. The vertical distance to the platform was 30 cm throughout the Utrecht tests.

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

Table 4-5: Trains in Utrecht (vertical distance refers to the steps from the train to the platform).

Train type	**Door width (cm)**	**Vertical distance (m)**	**N trains**	**N persons**
Two-storey intercity train	127	0.30	10	193
One-storey intercity train	107	0.30	2	75
International train	90	0.30	3	21
Local train	88	0.30	5	121
Local train	77	0.30	1	17
Local train	73	0.30	1	19
Sum			**22**	**446**

Table 4-6 shows the average flow as the total alighting time divided by the total number of people exiting. The last column gives the specific flow; the flow per metre door width (Interim guidelines, 1999).

Table 4-6: 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 4.17: People going in and out of the trains in Utrecht central station.

<u>Schiphol</u>

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 4-7. 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 4-7: Trains in Schiphol

Train type	Door width (cm)	Vertical distance (m)	N trains	N persons
Two-storey intercity train	140	0.30	1	16
Two-storey intercity train	127	0.30	1	16
One-storey intercity train	107	0.30	1	15
Sum			**3**	**47**

The flows are shown in Table 4-8.

Table 4-8. Flow results in Schiphol

Train type	Door width (cm)	Flow (pers/s)	Flow (pers/(s*m))
Two-storey intercity train	140	1.143	0.816
Two-storey intercity train	127	1.067	0.840
One-storey intercity train	107	0.682	0.637

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 4-9. 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 4-9: The train in the Best exercise.

Train type	Door width (cm)	Vertical distance (m)	N trains	N persons
Two-storey intercity train	127	0.70	1	86

The flows are shown in Table 4-10.

Table 4-10: Flow results of the Best exercise

Train type	Door width (cm)	Flow (pers/s)	Flow (pers/(s*m))
Two-storey intercity train	127	0.729	0.574

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 137 and 127 cm; the vertical distance to the platform was 30, 50 or 0 cm (see Table 4-11). 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 30 cm.

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

Table 4-11: Trains in Kastrup.

Train type	**Door width (cm)**	**Vertical distance (m)**	**N trains**	**N persons**
One-storey intercity train	137	0.50	1	20
Local train	127	0.30 / 0	6	119
Local train	127	0.30	1	30 (school class)
Sum			**8**	**169**

The flows are shown in Table 4-12. The train with the school class is excluded.

Table 4-12. Flow results in Kastrup.

Train type	**Door width (cm)**	**Flow (pers/s)**	**Flow (pers/(s*m))**
One-storey intercity train	137	0.952	0.694
Local train	127	0.717	0.564
Local train (school class)	127	0.441	0.347

Stockholm

Stockholm, the capital of Sweden, has a metro system comparable to the ones of London, St Petersburg and 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 alighting 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 4-13: The metro in Stockholm.

Train type	**Door width (cm)**	**N trains**	**N persons**
Metro train	120	4	77

The flows are shown in Table 4-14.

Table 4-14: Flow results in Stockholm.

Train type	**Door width (cm)**	**Flow (pers/s)**	**Flow (pers/(s*m))**
Metro train	120	1.588	1.221

Figure 4.18 shows one of the four tests.

Figure 4.18: Metro in Stockholm.

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.

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

Table 4-15: The results from the evacuation exercise in Stockholm.

Test	Door width (cm)	Vertical distance (m)	Flow (pers/s)	Note
1	120	1.2	0.1-0.2	No light in tunnel
2	120	1.2	0.4-0.6	Light in tunnel

4.3.2 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.

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 passengers, 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 4-16. The total number of persons is 462.

Table 4-16. The flow (pers/s) for different door width.

Test location	Door width (cm)	N persons	N tests	Time (s)	Flow (pers/s)
Utrecht	127	209	10	260	0.804
Utrecht	107	75	2	75	1
Utrecht	88	121	5	159	0.761
Utrecht	77	17	1	23	0.739
Utrecht	73	19	1	40	0.475

Figure 4.19 and Table 4-17 show the results.

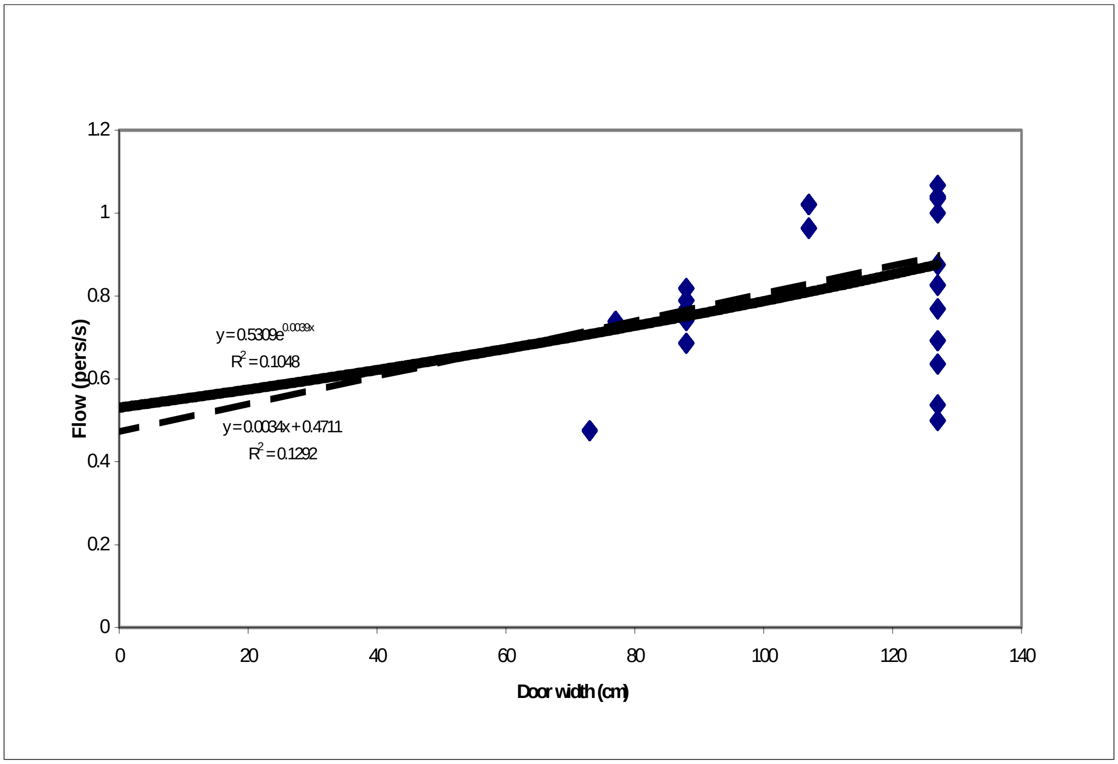


Figure 4.19: Flow as a function of door width (linear and exponential regression).

The R^2-values are generally low, 0.13 at most, indicating a weak relationship. The flow is almost the same for a train with 127 cm wide doors and a train with 88 cm wide doors. This issue will come back in the discussion.

Table 4-17. The regression of door width on flow.

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

Vertical distance

To estimate how flow depends on the stepping down distance to the platform, the results from Stockholm, Utrecht, Schiphol, Best exercise and Stockholm exercise were used, see Table 4-18.

Table 4-18. 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 4.20 and Table 4-19.

Table 4-19. 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 moderate correlation. According to the linear regression model, the flow comes to a stop (zero speed) with a vertical distance between 1.5 and 2.5 m. (According to the exponential model, the curve never reaches 0.)

The model underestimates the flow when there is no vertical distance. In Stockholm the mean flow was 1.59 pers/s whereas the model estimates a flow of 1.3 pers/s. This will come back in the discussion.

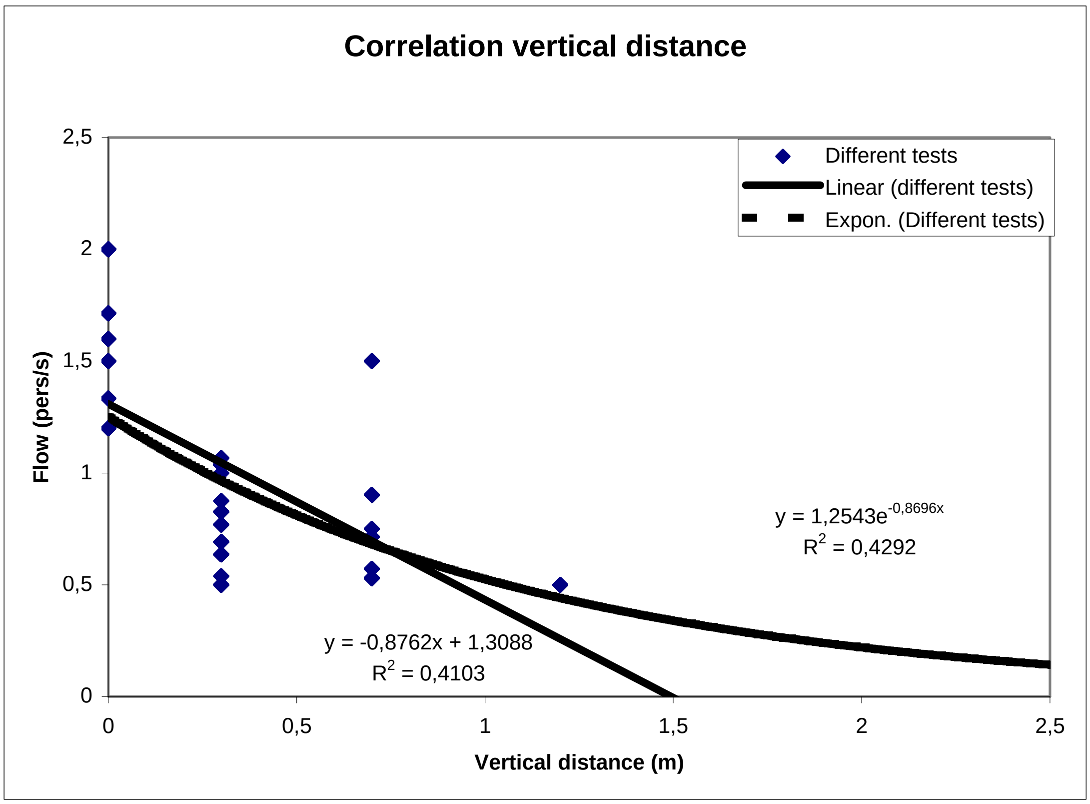


Figure 4.20: Flow as a function of distance to the platform (linear and exponential regression).

Luggage carrying

Regression analysis was not used to study the effects of luggage carrying because luggage carrying was a dichotomous variable; people carried, or did not carry, heavy luggage. We made no attempts to estimate the weight or the bulk of the 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 127 and 130 cm, which are to be considered 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 4-20. 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

<u>Combination of the factors</u>

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 137 cm instead of 127 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 4-21.

Table 4-21: 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'll come back to this issue in the discussion.

4.3.3 Discussion

Are the train data valid? Validity data is limited by the setting which was mostly normal egress and if emergency egress, then quite "staged" . Do people alight in the same way during a real emergency as they do in these rather normal settings?

Studies of people alighting from trains during real fires are not known to us, and no comparisons to real disasters can be made. Still, the results of the current study may well agree with the flow during a fire or after an accident. There are several reasons for this statement.

To be sure, people alighting from a train do not encounter the same stress as the victims of a disaster. Nevertheless, people alight as fast as they can in either case. Normal train passengers are eager to be fast, and are aware that there are many waiting behind them. If someone is blocking the door of the metro systems (especially at rush hours) that person will be "assisted" and pushed out of the train.

Lack of information poses a problem. Without information on the disaster, passengers would see the stop as an ordinary delay and wait (patiently or impatiently) until the train starts moving again. This would postpone evacuation. Assuming, however, that train personnel informs the passengers or that the passengers inform their fellows, everyone decides to evacuate already while still being seated. We believe that the validity of the data is satisfactory provided that the passengers have adequate information about the incident.

Are the train data also reliable? The people observed were for the most part random samples from the population of train passengers. Moreover, the data come from a range of (Northern) countries while the different test settings (such as door width) varied within each country. And the number of participants was rather large too. We believe that this makes the data in general reliable.

The result of the Stockholm exercise seems unreliable because the second test run was much faster than the first test run. Stockholm could be "atypical" because the vertical distance to the emergency platform was extreme (1.2 m). It is conceivable that the test participants did better the second time because they were "trained" during the first test run. Other reasons for a fast second test run are there was light in the tunnel during the second run and the train was less crowded.

Factors that are important for the flow at the doors were also revealed. A first finding was a flow that was almost constant regardless the width of the door (between 0.88 and 1.27 m). Bottlenecks earlier in the train could explain this finding. The corridor between the seats is usually smaller than the door and is therefore the real bottleneck. This is typical for longer-distance trains that are designed for comfort rather than for alighting. Another explanation is that flow cannot be completely linear with door width. Passengers alight two abreast, not 2½ abreast. An increase in flow requires probably doors wider than 1.27 m. Assuming passengers with a shoulder breadth of 0.5 m, doors of 1.5 m at least are required for a flow increase.

Another finding was the large negative influence of increased vertical distance between the train and the platform. Leaving a train that is level with the platform is much faster than leaving a train at some height above the platform. Even when carrying heavy luggage, alighting from a "level" train is still faster than alighting of unencumbered people from a train with a vertical distance of no more than 30 cm to the platform.

A last finding was slower egress when carrying luggage. An explanation in terms of increased space occupied is possible; the distance between the passengers increases and there is less space to alight side by side. An alternative explanation is slower movement because of increased weight.

There was an interaction between vertical distance and load carrying. Without heavy luggage, presence of a vertical distance reduces the flow to half of its original value; with heavy luggage, presence of a vertical distance reduces the flow to 70% only of its original value.

These and other findings are all quantified. For example: the best situation is no vertical distance at all. To evacuate 100 persons through a "standard exit" without vertical distance takes 60 seconds only. The second best situation is a vertical distance of 0.7 m at most. Evacuation of 100 persons through one exit then takes 120 seconds. With larger vertical distances, the situation becomes worse. Evacuation of 100 persons through an exit in Stockholm exercise takes 200 seconds and, for distances exceeding 2 m (plus or minus 0.5 m), the prediction is that the flow is very low; the estimated capacity of the exit approaching zero. 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.

4.4 Evaluation and recommendations

We come back to the stage model and on important results of the road tunnel and train tests. We summarise also the recommendations.

4.4.1 Stage model

Not all stage models can be used for observations from cameras. For example, the model of Passenier and van Delft (1995) cannot be used because the processes of the model cannot be observed. We used a simpler three-stage model assuming the perspective of a (camera) observer. All stages were easily observable.

The appropriateness of the model can be judged by the observed behaviour of the test participants. Did they act according to the model, or were there significant exceptions? That is, was it possible to describe all behaviour by the three-stage model or did people act completely otherwise over different occasions? The analysis revealed that very few acted in a way that did not correspond to the model. Most people sat in their cars, then stepped out, hesitated, and finally decided to evacuate. The stages seemed to represent behaviour adequately.

Approximation by cumulative density functions also seemed to be adequate. This strengthens our confidence that the model is an adequate representation of evacuation behaviours.

The moment of the announcement of the tunnel operator was very important; in most cases, it started the evacuation. In the road tests, the announcement came after 5-6 minutes. We conclude that an *early* announcement is important because the tunnel will be empty earlier. Also from the TNO driving simulator study we have learned that the operator announcement stresses the need for action. Without this announcement, less people claim that they would leave their vehicle and if they state they would leave, it takes a longer period of time before they realise they need to evacuate. What was not tested in the simulation was whether escalation of the fire would ultimately drive motorists out of their cars. In reality, police, fire-fighters or other rescue workers will arrive on scene, and start giving directions. However, this is already late in the process, and every minute that is saved before that is crucial.

4.4.2 Panic and information

The data confirm that panic is the exception rather than the rule in evacuations. There were no signs of either individuals or groups of people becoming panic stricken. Most people acted well planned and even though some were running to the exits they did not show any non-social behaviour. These conclusions are similar to the findings of e.g. Sime, discussed in Section 2.

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

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.

In this study conclusions have been drawn about the effect of information given as spoken messages via loudspeakers in the road tunnel. The quality of the information was not evaluated; there was only one message. It should be noted that *information only* was presented ("explosion danger") and that no instruction as to behaviour was given (as was done in the driving simulation study of TNO). Nevertheless, the authoritative statement about danger was sufficient to make people leave their car and go to the emergency exits.

It should be noted that this "dangerous" information led to orderly evacuation rather than to panic. This underlines what Quarantelli said "information is the antidote to panic" (1999).

4.4.3 Herd effects

Herd effects are said to be the effect on the individual's behaviour of surrounding people. In several reports (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. Herd effects are often mentioned in a negative sense. People cease to think independently and just copy blindly what others do. It should be recognised that the behaviour of others conveys useful and important information. Several others walking (or running) away suggests the presence of danger. Others disappearing through an emergency exit suggests that the exit offers refuge. Others trying in vain to open a door suggests a door that is inaccessible, etc.

In this study the herd effect has been evaluated from a statistic approach. The results underline its importance. It is obvious that the visible actions taken by other motorists is what makes others react; that is, one motorist stepping out of his car induces others to copy this behaviour.

Herd effects are probably important in evacuations from trains also. One passenger who goes and stands, collects belongings, and makes clear preparation for leaving the carriage may well set the example for others. Such behaviours were outside the scope of the present study.

4.4.4 Vertical distance

The effect on the flow of people through train exits was greatly affected by the steps between the platform and the train floor. This factor was more important than door width.

The effect of 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 section 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.

4.4.5 Walking speed

The average walking speed achieved in this study is 1.37 m/s, similar to Pauls' (1988) data of walking speeds between 1.2 m/s and 1.6. When comparing with values from 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 others are present. For example people evacuating alone from apartments may be affected of totally different factors resulting in different values of walking speed.

4.5 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 Section 2.

4.5.1 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 its 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.

4.5.2 The operator

This shifts quite a burden to the operator who is human, and subject to similar uncertainties as the people in the tunnel although at a different level. The operator does not hear or smell what is inside the tunnel, and the camera view is limited; for example, in a fatal collision in the Westerschelde tunnel (Sept. 2003) a car wreck was hidden by a large HGV. The operator can loose valuable time trying to assess the severity of the situation and hesitating. Thorough training seems required (Keating, 1985).

4.5.3 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 motorists 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 Section 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.

4.5.4 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.

4.5.5 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 Section 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 Section 4 for details) where there was no platform at all.

4.5.6 Carrying luggage

Evacuation is faster without luggage. Reasons are that loaded people occupy additional space, thus reducing the capacity of escape ways. Moreover, the load will reduce their manoeuvrability and slow them down. In case of an emergency evacuation, Austrian railways recommends passengers to leave their luggage behind. One cannot expect that many will follow this instruction but a few will do and, therefore, speed up the evacuation a little.

Modelling

The aim of the current study was to collect data for modelling evacuation behaviour and evacuation time in order to improve the CRISP evacuation model of BRE (see also next chapter). 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 road tunnel rather than the train tunnel because there are more data for the road tunnel.

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 4.21 shows the three stages.

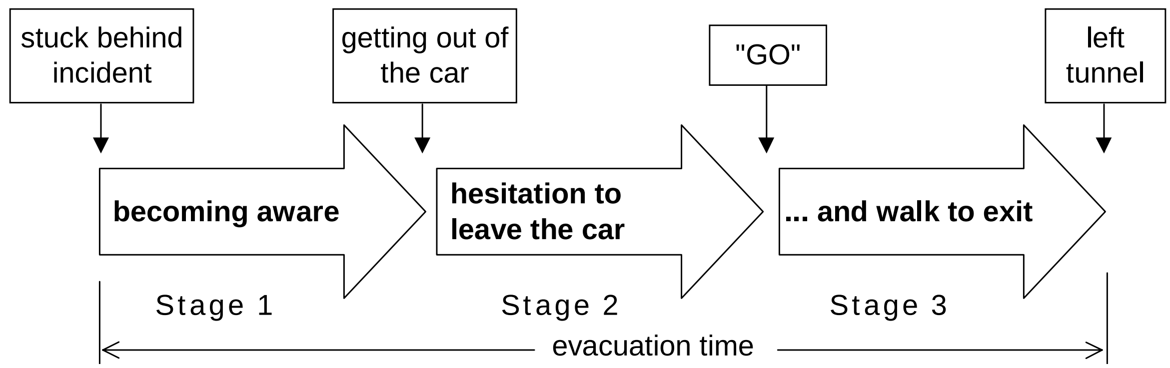


Figure 4.21: Three-stage model of a motorist who leaves a tunnel afoot after being stuck behind a burning HGV.

Figure 4.22 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.

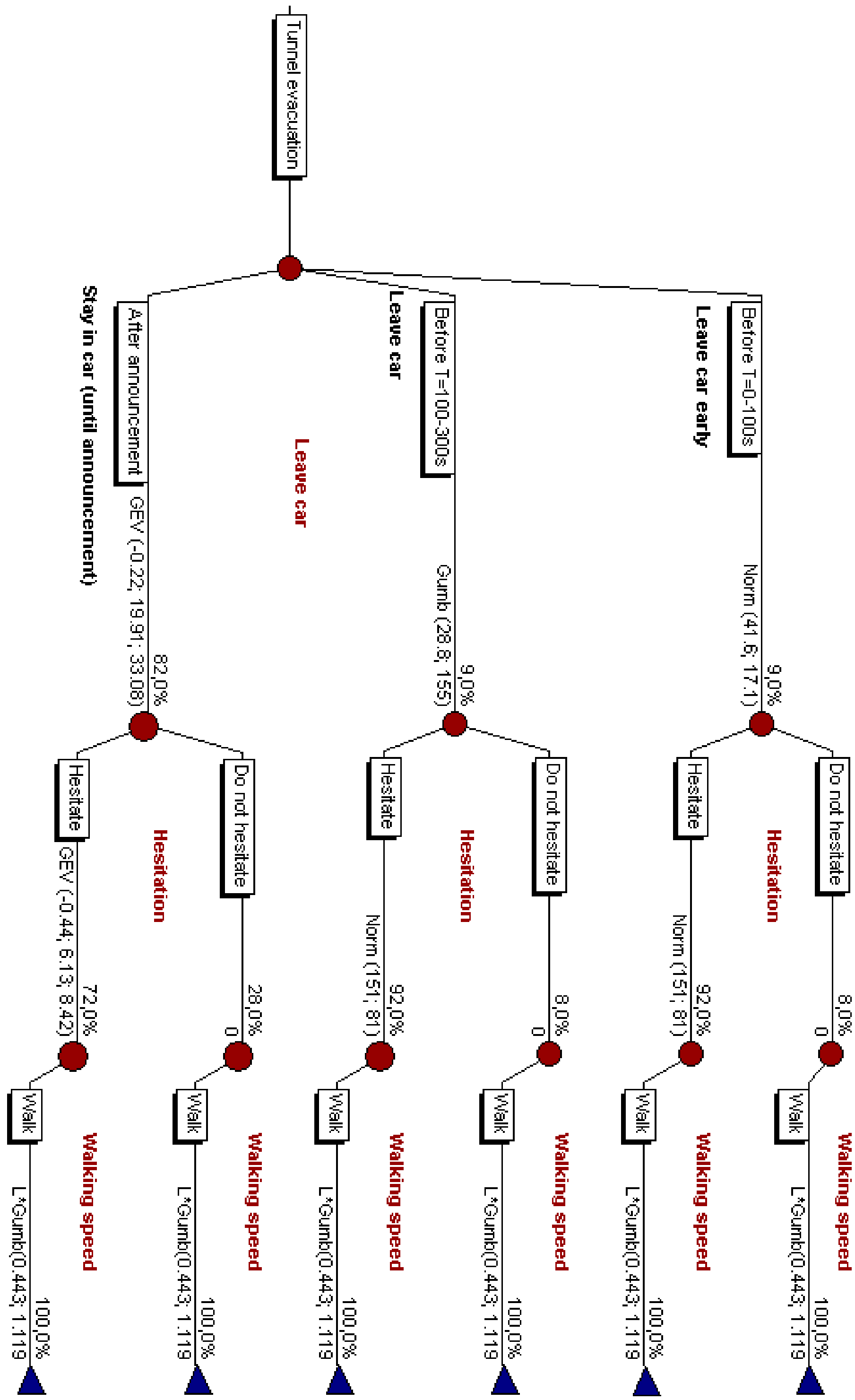


Figure 4.22: Event tree describing evacuation from a road tunnel.

An Example

To illustrate application of the model, we modelled a group of six imaginary motorists; two being aware almost immediately about the danger, two becoming aware with some delay, and the other two becoming aware only after the announcement of the operator. The distances they 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, who represent the fastest and the slowest possible motorists. For Mr. Fast and Slow, the distances to the nearest exit were set at 100 m.

In Table 4-22 the total evacuation times are shown.

Table 4-22: Evacuation times of a few (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

These examples give an idea about how long it takes to evacuate a tunnel.

In the graphs the position in the distribution of each stage is displayed for the examples described above.

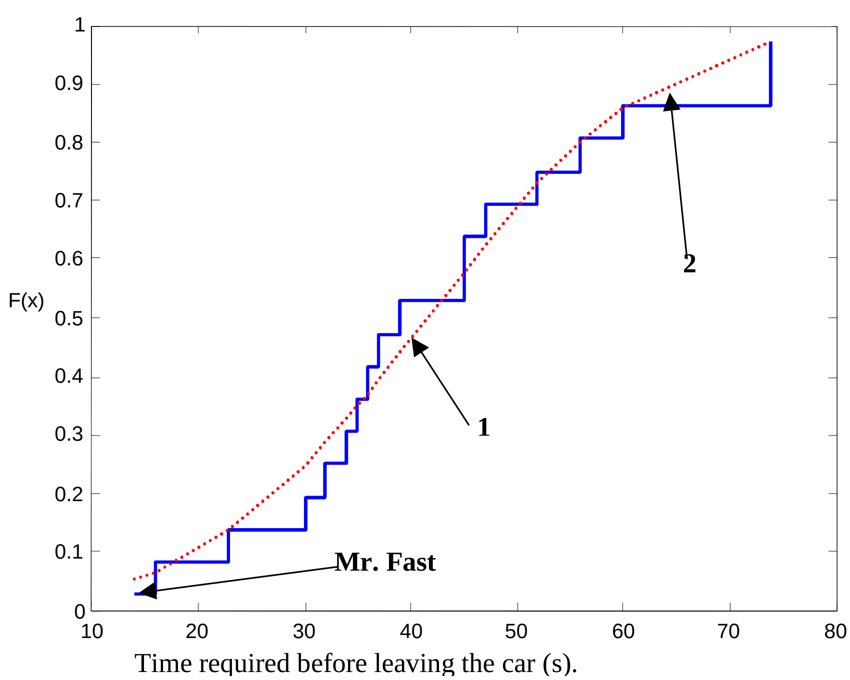


Figure 4.23: Awareness time for Motorists 1, 2, and Mr. Fast. (All are action-prone and react spontaneously, before the operator's announcement.)

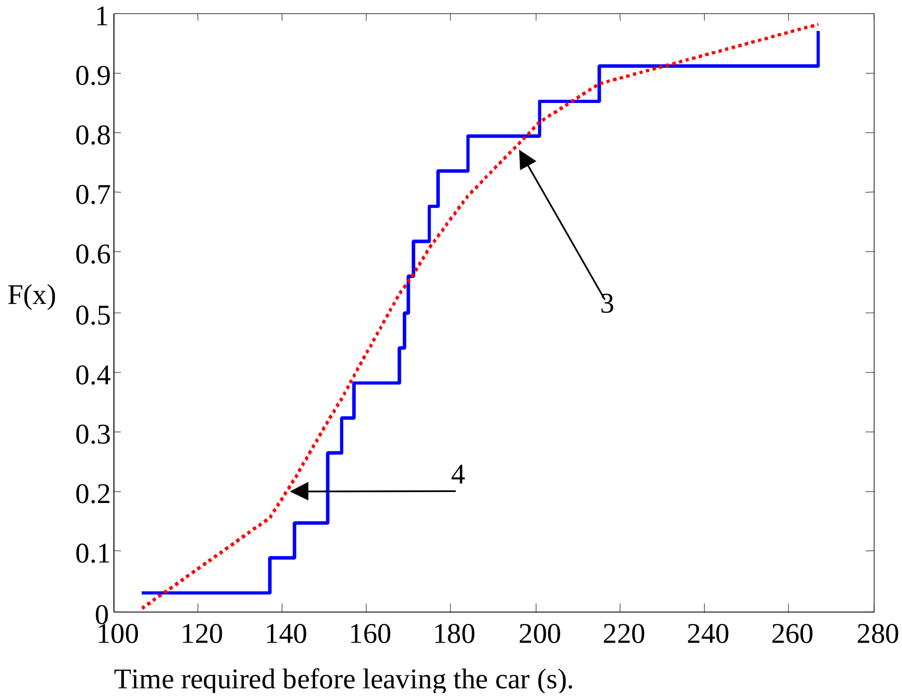


Figure 4.24: Awareness time for Motorists 3 and 4. (All are action-prone and react spontaneously, before the operator's announcement.)

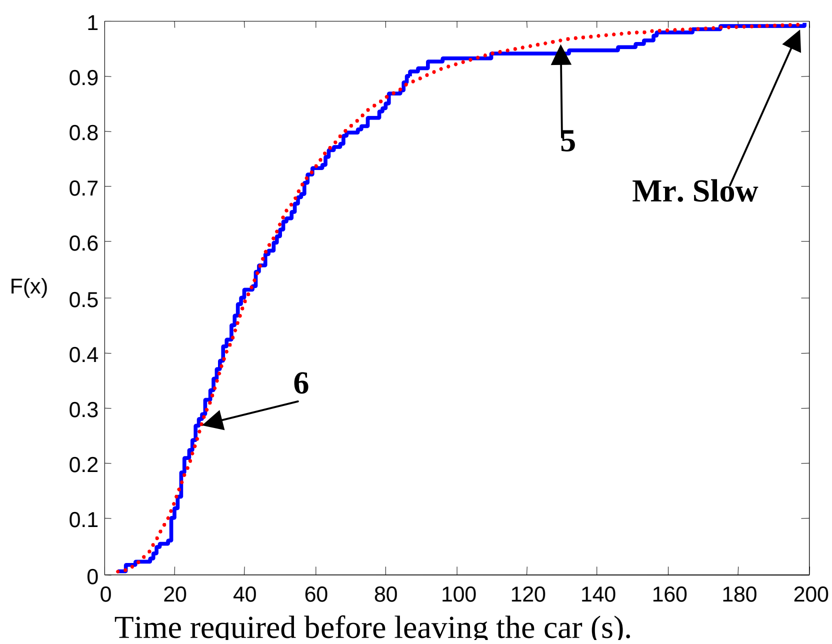


Figure 4.25: Awareness time for Motorists 5, 6, and Mr. Slow, all requiring the operator's announcement to get out of the car.

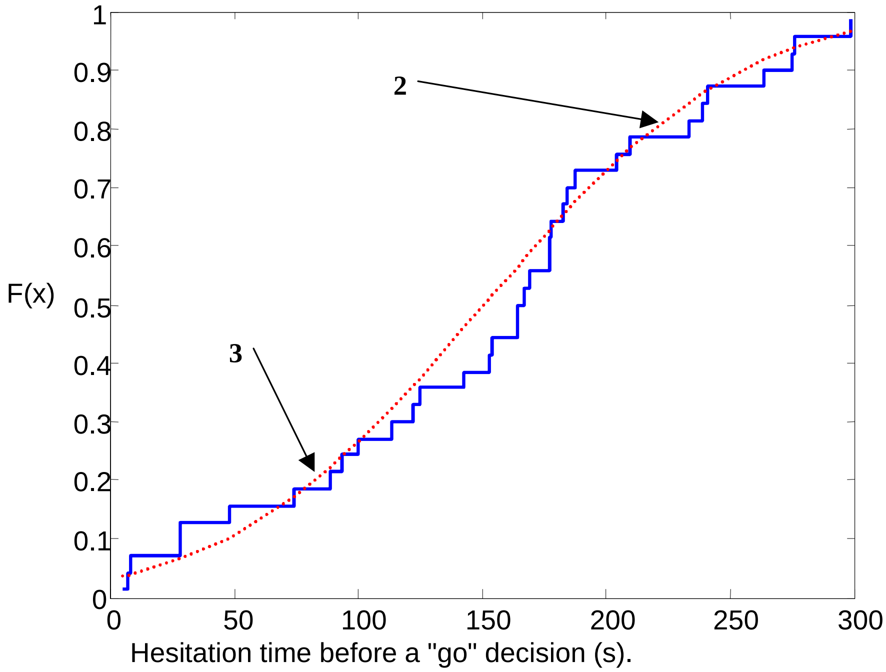


Figure 4.26: Time required for a "go" decision for Motorists 2 and 3. (Both needed the operator's announcement.)

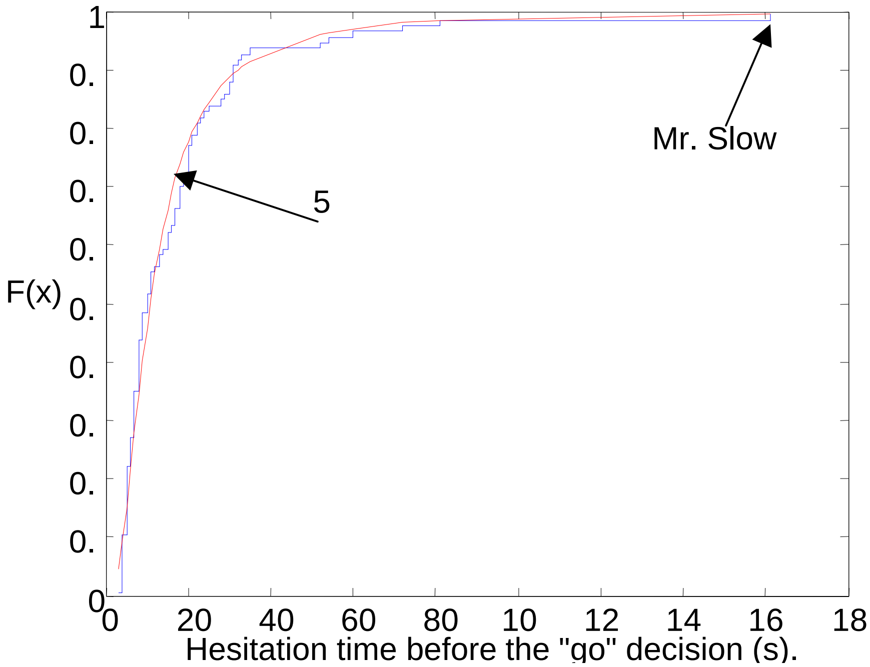


Figure 4.27: Time required for a "go" decision for Motorist 5 and Mr. Slow. (Both needed the operator's announcement.)

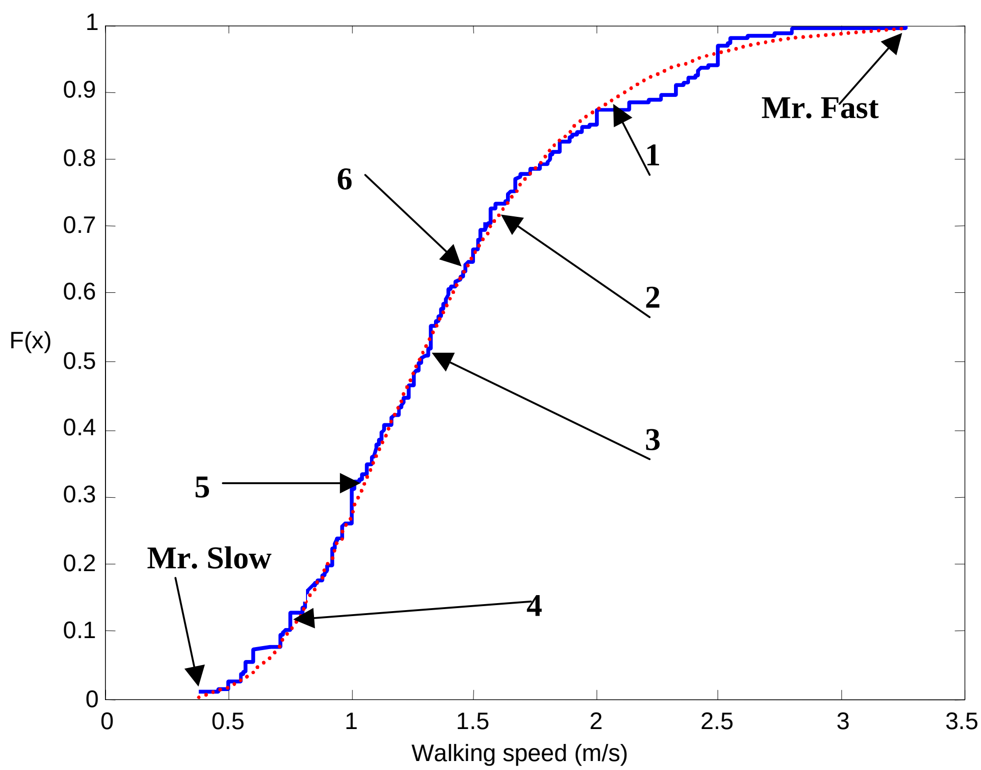


Figure 4.28: Walking speeds of all 8 motorists.

4.7 General Discussion

The data collected can be used to model the evacuation of larger groups of people in, especially, road tunnels. The model can be used for a worst-case scenario analysis as, for example, "Mr. Slow" (Figures 4.25 and 4.27). It should be noted that some model distributions end at infinity which is real slow. This could happen in reality when a person really cannot walk. A practical approach is to accept 1 or 2% "strayers" without judging the evacuation safety as insufficient.

The thus obtained evacuation times can be compared to the time available to answer the critical question whether there is sufficient opportunity to evacuate. The time available depends on the scenario and in particular on the escalation of the incident. Smoke and heat are generally tolerable during the first 5 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? The current modelling ignores group effects by treating the group as a number of individuals, each of them randomly assigned to one particular reaction type. The probability of an individual being assigned to the "immediate reaction" type is small, reflecting the empirical observations. An alternative way of modelling is to assign all motorists *as a group* to one, and only one, reaction type; for another follows where one sheep goes. Again reflecting the empirical observations, the odds that the whole lot is assigned to a "passive reaction" type is quite large. They will stay in the car until the call of the operator.

As said before, less can be said about evacuation from a train tunnel because we collected less data about trains. The current data permit accurate estimation of the flow of passengers through the train exits, that could well be the bottleneck. It was revealed that the flow depended strongly on the vertical distance to the platform and, somewhat less, on the luggage carried. There are no data on awareness time and hesitation time.

When evaluating the design of tunnels on evacuation safety it is important to compare the evacuation time required with the time available, for example the period when there is not yet a high density of toxic smoke and heat is not yet unbearable. When a tunnel is designed, such analyses should be made to see whether time available matches with evacuation time. Evacuation safety is poor if there is no match, and measures are required. The current data underline the high efficiency of early and adequate public announcements; of more or wider emergency exits; and of escape ways without steps.

5. SELF-EXPLAINING SOUND BEACONS IN EVACUATION

L.C. Boer & S.J. van Wijngaarden
TNO Human Factors, Soesterberg, the Netherlands

Partly because of additional funding from RWS (NL), Boer and van Wijngaarden (2004; Boer and van Wijngaarden, in press) were able to perform some extra evacuation studies that are of primary importance to the UPTUN project. The aim of these studies was to assess the effects of directional sounds on evacuation behaviour.

5.1 Introduction

Smoke takes vision away, but does not affect hearing. Sound beacons were developed in response to the need to provide people orientation and guidance in smoke (Rutherford and Withington 1998). The beacons were designed to emit signals that are localized easily.

Previous studies reveal that the system of Rutherford and Withington (RW) is effective for over 90% of the participants (Directional sound evacuation 2001, 2002; Withington 2002). There is a condition: the participants need to briefed about the system <u>and</u> need a short demo of the type of sound played by the beacons. With briefing only, and no sound demo given, the effectiveness of the system was down to 70% of the participants (Boer and Withington 2004). When briefing was also omitted, the effectiveness dropped to 20% of the participants (Boer and Withington 2004).

One may assume that the public will soon learn to understand what the beacons mean when the beacons will be applied universally: in buildings, airplanes, tunnels, etc. Europe has already buildings with sound beacons as a means of identifying escape exits, and the international maritime organization IMO is considering a similar use of beacons onboard passenger ships. Assuming, in the next decade, the gradual introduction of the sound beacons in buildings, theatres, tunnels and all kinds of transportation, the meaning of the beacons could become common knowledge. The need for additional instructions would disappear. But awaiting such universal application of sound beacons, reality is that disasters leave little opportunity for advance briefing and sound demonstration. It is therefore desirable to have a system that is effective even without advance information--a so-called self explanatory (SE) system. Is such a system possible? The paper describes development and testing of such a system.

5.2 Design criteria

Our design criteria for new sound beacons were: localizability, audibility, self explanation, saliency, and minimum interference with other communications. The criteria are interrelated and sometimes conflicting, and serve as guidelines rather than as principles that inevitably suggest a specific solution. We discuss the criteria one by one.
The criterion of localizability can be met with a suitable spectral and temporal structure of the signal, utilizing the knowledge of the human auditory system. Humans are able to localize signals with an accuracy of five degrees (Makous and Middlebrooks 1990), basing their judgment on: (a) interaural time difference, (b) interaural level difference, and (c) spectral characteristics. The first two cues are known as binaural cues because they make use of the fact that humans have two ears. Signals emanating from either

side of the mid-line will arrive first at the ear closest to it and will also be loudest at that ear. The last cue, spectral characteristics, is related to the direction from which signals reach the ear. As a result of passing over the bumps or convolutions of the pinna, some frequencies are attenuated while others are amplified. These spectral characteristics are most marked at frequencies beyond 2000 Hz. The ideal signal should include a wide frequency range (up to 16 kHz or beyond), and have a sufficiently close spacing of frequency components. Pulses, clicks, and sharp onsets also enhance localizability.
In many natural circumstances, signals have reflections or echo's. Humans perceive the sound travelling straight to the ear first and, secondly, the sound travelling to the ear after one or more reflections. The energy of the direct path reaches the ear a fraction earlier than the energy of the indirect path(s). The informational contents of the direct path and the indirect paths are so similar and their time difference so small that the information fuses into one coherent percept. Humans will locate the origin of that percept from the information that reached the ear first, a phenomenon called the precedence effect.

There is a wealth of literature on spatial hearing that helps in designing signals for localizability (e.g. Blauert 1997, Langendijk 2002; Langendijk and Bronkhorst 2002; Wesley Grantham 1995). The signal of the RW system consist of square-wave modulated thermal noise with a modulation frequency of 5-10 Hz, and a spectrum that is (approximately) flat on a logarithmic scale. The signal has good localizability.

The second criterion for sound beacons is audibility. This is an "easy" criterion; it can be met by turning up the sound level. For danger signals and warnings, ISO 7731 recommends a signal-to-noise ratio of 15-25 dB. This recommendation cannot be followed always because it would make the evacuation beacons too loud in very noisy environments. Such extreme loudness may only add to the confusion. Another way to increase audibility is to use signals that are different from background noise.

The third criterion for sound beacons is self explanation, here defined in terms of evoking the desired evacuation behaviour, even when people have no information whatever about the sound beacons. In the context of evacuation, self explanation suggests signals that attract people. This excludes harsh and dissonant signals. Attractiveness may also exclude signals with too many high frequency components.
The fourth criterion for sound beacons is saliency, the degree of attention the signal will attract. This is a subjective concept, measured or verified through listener panels. Signal characteristics that enhance saliency are tonality (as opposed to noise), roughness, and loudness.

The last design criterion for sound beacons is minimum interference with other auditory communications in the environment such as: general public addresses, directives of rescue workers, and contacts among evacuees. Minimal interference can be reached by allowing periodic lapses of silence (pauses) into the signal. This is especially effective for speech that, due to its redundancy, is rather robust against intermittent interruptions through interfering sounds (Bronkhorst 1999). An obvious alternative is reducing the loudness of the beacon signal but that conflicts with audibility.

5.3 Self-explaining sound beacons

The new beacon signal consisted of the spoken message "exit here" preceded by dinner-bell sounds. The dinner-bell sound was a chime-like sequence of two harmonic bi-tonal complexes, starting with a 200-ms C plus E complex (fundamental frequencies 262 and 330 Hz) and, after a silence of 200 ms, a 200-ms E plus G complex (fundamental frequencies 330 and 392 Hz) followed by a silence of 200 ms. Thereafter, the message “exit here” was played in 1200 ms followed by a silence of another 1200 ms. Figure 5.1 shows the structure of the signal: 800 ms of chimes (50% of which silence) and 2400 ms of speech (again 50% of which silence). A full cycle took 4 seconds. The relatively long periods of silence (50% silence) helped to minimize interference with other communications, design criterion 6.

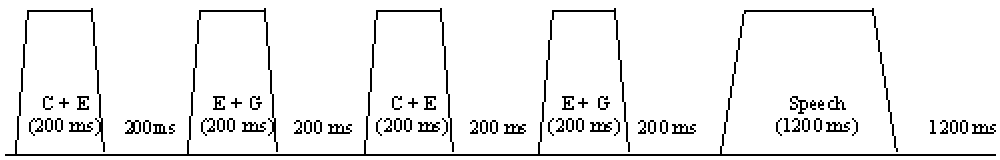


Figure 5.1: Temporal structure of the self-explaining sound, total cycle 4 s.

The spoken message was intended to suit the expectations of people in distress, who are looking for refuge: "There is an exit, and that exit is where you hear me calling". A suitable voice is important. We choose a male voice able to convey determination and urgency, while avoiding threatening or casual undertones.

Chimes were preferred over noise-based signals partly because they prepare people for a spoken message because people are familiar with public addresses preceded by such tonal sounds. Tonal sounds also have the advantage of being more salient than noise, thus increasing the probability that the chimes will be perceived even in a noisy environment. Noise-based signals, on the other hand, do not induce people to expect a message; rather, they are taken for working machinery (steam engine, pneumatic sounds) or mechanical failure (lost radio contact, pressure leak). People may dismiss such signals as irrelevant or even dangerous.

We selected simple chimes in order to avoid association with computer games. At the same time, we took care to avoid association with warnings such as fire alarms, because they could drive people away rather than attracting them. For the same reason, frequency sweeps were not applied (which on themselves would have enhanced both saliency and localizability).

Localizability was ensured by clipping the spoken text at 6 dB below the peak level, thereby decreasing the crest factor, and increasing the high frequency energy content. Moreover, after clipping, the speech spectrum was tilted (through digital filtering) to make the spectrum flat on a logarithmic scale.

Localizability of the chimes was improved by making the onsets maximally sharp; no tapering applied. The tone complexes contained all harmonics of both fundamental frequencies up to 20 kHz, with the individual harmonic attenuated 3% compared to the next-lower harmonic. The latter reduced the harshness or unpleasantness of the sound.

5.4 Plan of the study

The self-explaining system was tested once in a ship's interior and another time in a road tunnel. In the ship's interior, the SE system was compared with the existing RW system using two separate groups of participants (2 x 68 individuals). In the road tunnel, only the SE system was tested using 78 individuals, the data were compared to those collected by Boer and Withington using the RW beacons (2004).

5.4.1 Ship's Interior

The aim was to compare the effectiveness of the RW and the SE beacons in the situation that participants were not given any advance information about the existence of the beacons (just a general instruction "find refuge"). Effectiveness is defined here as the proportion of participants finding the escape route. The study included the coding of successive beacons because it constitutes a major challenge for guidance in a complex environment. When smoke takes vision away, there is a risk that evacuees, after walking

from Beacon A to Beacon B, will lose their bearings, and return to A. The system of Rutherford and Withington uses pulse frequency for coding successive beacons (e.g., 5, 7.5, 10, 12.5, 15 Hz); all evacuees have to do is to go to the beacon pulsating with the highest frequency. This is a natural tendency according to Rutherford and Withington. For the SE beacons, we used the precedence effect to code successive way points.
We tested the two systems at a T-crossing with beacons at either side emitting their signal. For the RW system, the beacon at the "correct" side pulsated more frequently than the beacon at the "wrong" side (7.5 *vs*. 5 Hz). For the SE system, the beacon at the "correct" side emitted its signal a tiny fraction earlier than the beacon at the "wrong" side. For both systems, a sound *vs*. silence condition was included: only the beacon at the "correct" side active, and silence at the "wrong" side.

<u>Methods</u>

<u>Subjects</u>. 136 participants were selected by a model services bureau with the vague information of "judging a ship's interior". There were no hearing requirements. Further instruction was provided at the start of the test, however, without making any reference to "sound beacons" or "sound system". Their ages ranged between 16 and 85 years with an average of 43 years.
<u>Test facility</u>. There was an imitated cabin area of a ship 9.6 x 7 m with small corridors and a cabin--see Figure 5.2. "Engine sound" was played in the background. Separate cone-shaped loudspeaker horns were mounted on the ceiling near the points A, E en C, directed towards the approaching test participant. They either played the RW signal (pulsating shhussing noise) or the SE signal (chimes and "exit here"). The conditions for coding successive beacons were: sound versus silence (condition 1) and sound versus sound (condition 2). The sound versus sound condition had the "correct" beacon pulsating faster than the "wrong" beacon for the RW system; for the SE sound, the signal of the "correct" beacon preceding the signal of the "wrong" beacon. A third condition was route: EC or route EA. Together, this created the 8 conditions of Table 5-1.

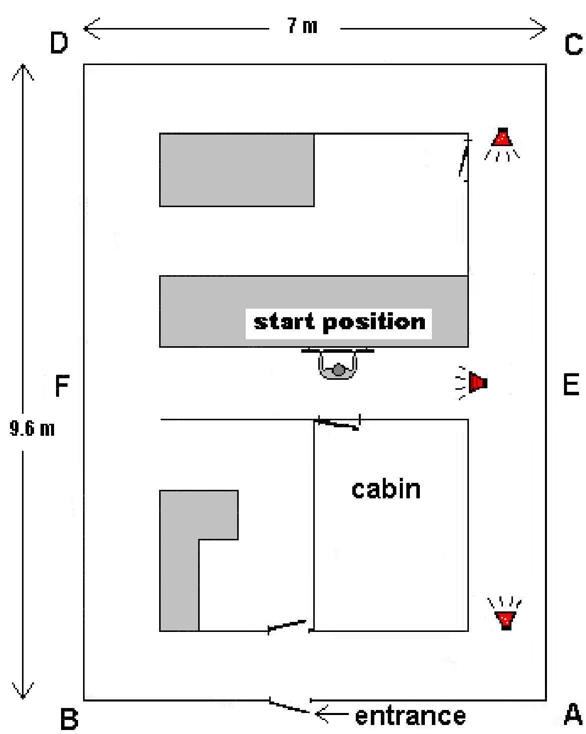


Figure 5.2: The ship's interior. (The participants are supposed to turn right to E, then right or left as directed by the beacons at A or C.)

Sounds. The signal of the RW beacons was square-wave noise with a modulation frequency of 5 Hz and a duty cycle of 75%, perceived as a rapid sequence of noise bursts with sharp onsets. Close to the loudspeaker, the spectrum approximated pink noise in the 100–16,000 Hz frequency range, but with a dip around 4 kHz and peaks around 1 kHz and 8 kHz. The spectrum was essentially flat on a logarithmic frequency scale, and sloped down on a linear frequency scale. The pulsation made the signal more salient in (nonpulsating) background noise.

Table 5-1. The eight sound conditions (17 participants per condition, total n = 136).

Route		Beacon @ E	Beacon @ C	Beacon @ A
RW silence [1]	**E to C**	**Noise, 5 Hz**	**Noise, 7.5 Hz**	**--**
	E to A	**Noise, 5 Hz**	**--**	**Noise, 7.5 Hz**
RW direction	**E to C**	**Noise, 5 Hz**	**Noise, 7.5 Hz**	**Noise, 5 Hz**
	E to A	**Noise, 5 Hz**	**Noise, 5 Hz**	**Noise, 7.5 Hz**
SE silence [2]	**E to C**	**"exit here"**	**"exit here"**	**--**
	E to A	**"exit here"**	**--**	**"exit here"**
SE direction	**E to C**	**"exit here"**	**"exit here" (precedent)**	**"exit here"**
	E to A	**"exit here"**	**"exit here"**	**"exit here" (precedent)**

[1] RW = beacons of Rutherford and Withington
[2] SE = self-explaining beacons "exit here"

Procedure. The individual participant was allocated to one of the 8 test conditions of Table 4-23. The poor visibility under conditions of dense smoke was simulated by safety goggles made opaque. We explained to the participants that the goggles imitated dense smoke. Blindfolded this way, the participant was escorted into the ship's interior and "parked" along the wall of the EF corridor, hands on the handrail. The test assistant explained that the participant should find the way to the assembly station at the captain's call. The test assistant then hid himself in the cabin. The "captain" activated the beacons, dimmed the overhead lights, and asked the participant on the intercom to go to the assembly station.
The test run was aborted when the participant turned away from the Beacon E, and reached corridor BF rather than corridor AC. The test run was complete when the participant reached either point A or C.

Results

Test participants walked slowly and hesitantly. Many took their time before getting into motion at all, went with their hands outstretched, trying to feel the way out. A few bumped (gently) against the wall at point E.
With the RW beacons, 40 out of 68 participants (59%) went to E (correct); the others went to F (incorrect). With the SE beacons, 63 out of 68 participants (93%) went to E. A test for difference between proportions revealed a significant difference ($p < 0.01$).
The remaining participants (40 and 63) had to take the T-crossing at E. With the RW beacons, 21 out of 40 participants (53%) walked in the intended direction. This is not different from random way finding ($p = 0.7$). With the TNO beacons, 54 out of 63 participants (86%) walked in the intended direction. This is significantly better than random way finding ($p < 0.01$).
At E, half of the participants walked under sound-sound conditions; the others under sound-silence conditions. With the RW beacons, 24 participants walked under the sound-silence condition. Eleven of them (or 46%) went into the intended direction. With the SE beacons, 32 participants walked under the sound-silence condition. Thirty of them (or 94%) went into the intended direction. The difference between these proportions (46 vs. 94%) was highly significant ($p << 0.01$).

The remaining participants walked under sound-sound conditions. With the RW sound-sound condition, 8 out of 16 participants (50%) went towards the more frequently pulsating beacon. In the SE sound-sound condition, 24 out of 31 participants (77%) went into the direction of the precedent beacon, a result definitely beyond random way-finding ($p < 0.01$). The difference between these two proportions, 50 for the RW system and 77% for the SE system, was probably significant (probability of nonsystematic or "random" result = 0.07; two-sided test). Table 5-2 summarises the results.

Table 5-2. Results of the different sound conditions, ship's interior ("*24 / 34 (71%)*" means "*24 out of 34 participants OK, or 71%*").

	choice location .		**Whole route correct**
	At start	**T-crossing at E**	
RW sound-silence [1]	**24 / 34 (71%)**	**13 / 24 (54%)**	**13 / 34 (38%)**
RW sound-sound	**16 / 34 (47%)**	**8 / 16 (50%)**	**8 / 34 (24%)**
SE sound-silence [2]	**32 / 34 (94%)**	**30 / 32 (94%)**	**30 / 34 (88%)**
SE sound-sound	**31 / 34 (91%)**	**24 / 31 (77%)**	**24 / 34 (71%)**

[1] RW = beacons of Rutherford and Withington
[2] SE = self-explaining beacons "exit here"

Informal conversations after the test runs revealed that at least two participants couldn't follow the English of the SE beacons with some participants misunderstanding "exit here" for the homophone "ik zit hier" [Dutch: "I'm sitting here"], and that at least three participants had hearing deficits.

Discussion

In poor visual conditions, and without any advance information, the self-explaining system was more effective than the system of Rutherford and Withington. Over 90% of the participants performing with the SE system found the escape way as opposed to about 50-60% of the participants performing with the RW system. Considering that, in the test situation, 50% is chance performance, we conclude that the RW system did not provide guidance at all.
A natural limitation as to the effectiveness of sound beacons using speech is lack of linguistic capability. A few of the Dutch participants failed to understand the "exit here" sound. Improvement is possible with bilingual beacons, alternating between "exit here" and "uitgang hier" [the native language for a Dutch population]. This improvement was made in the second test.

5.4.2 Tunnel test

Methods

The methods were those of Boer and Withington (2004) but only SE evacuation beacons were used, alternating between "exit here" and "uitgang hier" [Dutch], total cycle 8 s (see Figure 4.31). The test location was a tunnel tube slightly smaller (6.6 m) than the one used by Boer and Withington (10 m).
Participants and instruction. Seventy five new participants were selected with the information of "escape from a tunnel in dense smoke". They were in good health (self assessed) and had a driving license. Again, there were no hearing requirements. The age range was 18-75 years, 37 years on average.
At arrival at the test location, the participant read (and signed) a leaflet “You will get out from the bus in the tunnel in dense smoke. Your task is: get out of the smoke, get to safety. You are on your own. Don’t wait for others, don't offer assistance to others, don’t ask others for help. Do whatever you feel is best.".

Note that no reference was made to "sound beacons" or "emergency exits" (25% of regular tunnel users does not know that there are emergency exits, Krul and Boer 2002).
Location, apparatus and supervision. The test was in the C-tube of the Benelux tunnel in Rotterdam. The tunnel is 1 km long and 6.6 m wide with one lane of 3.5 m. The test area was halfway down the tunnel, around exits 6 and 7, 50 m apart (see Figure 5.3). Chains stretching over the roadway 25 m beyond these exits fenced off an area of 100 m x 6.6 m. SE sound beacons were mounted above exits 5 and 6, and above the neighbouring exits (4 and 7).

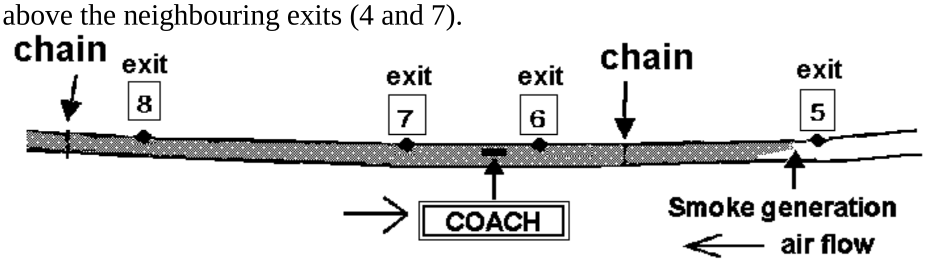


Figure 5.3: The layout of the tunnel test. (Exits 8-5 carried sound beacons; chains fence the test area off.)

The exits turned in the direction of the flight and were self-closing. Their threshold was about 50 cm above the roadway. A step 30 cm high and a tread of 25 cm gave access to the door. Step, threshold, and door were 108 cm wide; the net door aperture was 90 cm x 200 cm. The doors could be opened with a normal door-handle.
A bus with 50 seats was used to transport the participants to and from the tunnel. The side and rear windows were made opaque to prevent the passengers from having an outside view.
Test assistants were posted at both chains and at the exits 6 and 7. A thermal imaging camera was mounted 2 m high, 16 m after exit 6, looking towards the bus. Figure 5.4 gives an idea about the view of the camera.

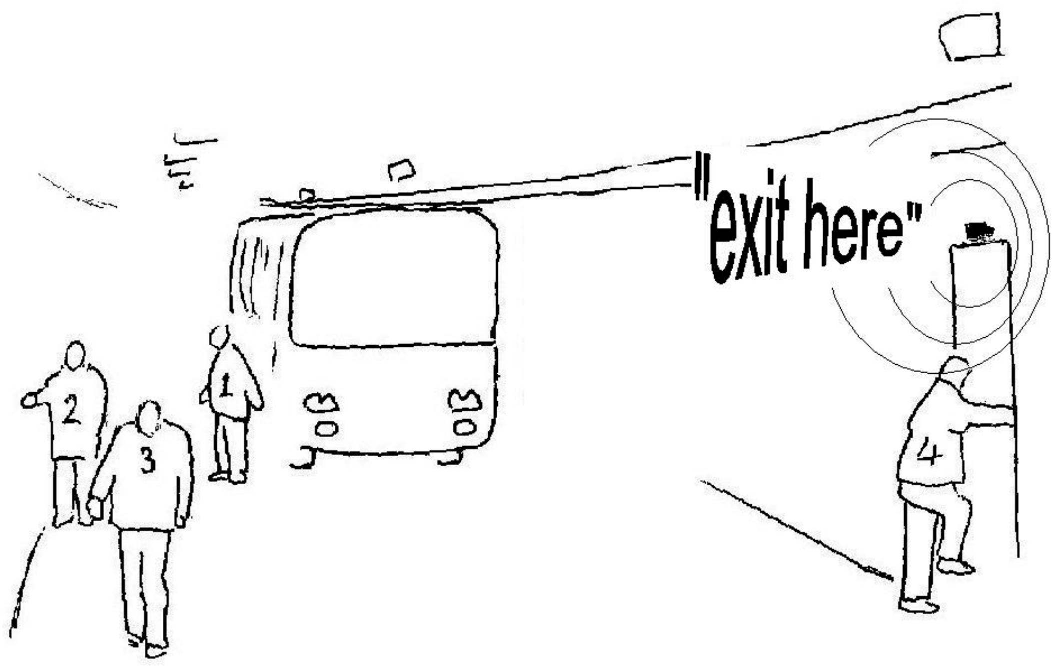


Figure 5.4: Camera view: after alighting (1), the participant makes contact with the wall (2), starts walking along the wall (3), then crosses over to the exit (4) where the beacon is calling

"exit here".

Smoke generators at exit 5 produced white "cosmetic" smoke. The airflow transported the smoke to the test area at a speed of about 0.3 m/s. The participants carried simple smoke masks over nose and mouth. Vision was 1–2 m at first and decreased to ½ tot 1½ m later on.
Procedure. The participants arrived in two groups; the first group (n = 33) around 20:00 h, the second group slightly after 21:00 h (n = 42). Upon arrival, each participant received an instruction leaflet. Participants were escorted to the bus where they read and signed the leaflet. Meanwhile, the bus drove them over to the tunnel. During the ride, the instruction was repeated and questions could be asked.
At the test location, the bus stopped with the front door 32 m beyond exit 7 and 18 m before exit 6. The participants left the bus one by one, at fixed intervals of 40 s. Directly before alighting, the participant donned the mask. Alighting lasted about 25 minutes for a group. Six minutes after the last participant had left the bus, the test was over and the test assistants escorted all participants back to the bus.

Results and discussion

Almost all participants walked into the direction of the bus ride, a few after hesitating over backward or forward direction. Forty-two participants (or 56%) went straight towards exit 6, crossing the roadway slantwise. The other half (44%) searched contact with the (right) wall first, using a mixture of touch and visual contact. After walking some distance along the wall, they oriented their head towards the left and some held their pace or even stopped. Then, they crossed over except for 10 participants who, apparently, decided to continue along the wall. These participants ended at the forward chain.
Table 5-3 shows the number of participants finding an emergency exit, and the number of participants "collected" at a chain across the roadway 25 m beyond an exit. For comparison, the data of the RW beacons (those conditions where advance information was omitted), are included.

Table 5-3. Results of RW beacons (Boer and Withington, 2004) and SE beacons (number and percentage of people arriving at the four possible endpoints), tunnel environment.

	driving direction →			**→**	
test	**chain 1**	**exit 7**	**BUS**	**exit 6**	**chain 2**
RW beacons [1]	**29**	**7**		**5**	**24**
(n=65)	**45%**	**11%**		**8%**	**37%**
SE beacons [2]	**0**	**1**		**64**	**10**
(n=75)	**0%**	**1%**		**85%**	**13%**

[1] RW = beacons of Rutherford and Withington
[2] SE = self-explaining beacons "exit here"

To assess the effectiveness of the SE and the RW beacons, the data were summed once for escape in the backward or the forward direction (backward = first chain + exit 7; forward = exit 6 + last chain) and another time for escape through emergency exit vs. escape over the roadway (emergency exit = exit 7 + exit 6; roadway = first and last chain) seeTable 5-4.

Table 5-4. Results of RW and SE beacons (summarized from Table 5-3) tunnel environment.

test	direction of escape* backward	forward	destination exit	roadway
RW beacons [1] (n=65)	**36 55%**	**29 45%**	**12 18%**	**53 82%**
SE beacons [2] (n=75)	**1 1%**	**74 99%**	**65 87%**	**10 13%**

*** relative to direction of driving**
[1] RW = beacons of Rutherford and Withington
[2] SE = self-explaining beacons "exit here"

With regard to the walking direction, all of the current participants (except for one) went forward (99%). By contrast, the participants of the previous test (with the RW beacons) showed no directional preference; 55% went back, 45% forward. The difference with the current test with SE beacons is highly significant ($p<0.001$, test for difference between proportions). We interpret this as a preference to walk to the nearest (loudest) beacon--a preference that operates only when the beacon is explaining itself.

With regard to the final result--escape through an emergency exit marked with a SE beacon--, 65 out of 75 participants or 87% left the tunnel tube by an emergency exit. By contrast, of the participants of the previous test only 18% left the tunnel tube by an emergency exit marked with an RW beacon. The difference is highly significant ($p<0.001$, test for proportions). When there is no advance instruction about sound beacons, they are effective only if they explain themselves.

In reality, an effectiveness beyond 87% seems justified for the SE beacons. In the test, all participants alighted along the wall without emergency exits. They had, therefore, to cross the roadway in order to reach an emergency exit. Fear seems a likely reason for participants to continue along the wall (despite orienting the head towards the opposite side); the wall offers orientation and safety under poor visual conditions. In reality, about half of the motorists trapped in smoke would alight along the other wall--the one containing the emergency exits. Probably all of them would find the emergency exits. This predicts an overall effectiveness of 94% for the SE beacons (87% for those along the "wrong" wall and 100% for those along the "correct" wall).

With the SE beacons, participants reached the emergency exit in 23 s on average. Considering a distance of 20 m, that is a walking speed of 0.9 m/s, roughly twice as fast as the 0.44 m/s observed with the RW beacons (Boer and Withington, 2004).

5.5 General discussion

The current tests show very effective (> 90%) auditory guidance under conditions of poor visibility, given that the sound used for guidance suits the expectations of the evacuees. Our self-explanatory sound beacons called "exit here" preceded by a dinner bell sound. Even without advance instruction, they offered help to test participants looking for refuge and a way out. In real calamities, one may assume that humans trapped in dense smoke will, similarly, be looking for refuge and the way out and that the SE sound used here will suit the expectations as well. Additional testimony to the efficiency of the SE beacons was the observation that all participants except one went to the nearest emergency exit. This was 55% in a previous test with a beacon sound that was not self explanatory (Boer & Withington, 2004).

The test in the ship's interior showed that the "shhussing" sound beacons of Rutherford and Withington (1998) failed to guide people adequately; their way finding was random. A test of Boer and Withington (2004) in a road tunnel showed that less than one-fifth of the participants found the emergency exits. We conclude that the particular sound did not suit the expectations, and that the RW system will be effective only if evacuees are informed in advance about the sound and its meaning.
Hearing deficits are a natural limitation on the effectiveness of any sound beacon. About one fifth of the population has hearing problems of a degree (Shields & Boyce 1995, table 3, data for public bus and private cars). It is also known that the number of people with hearing deficits increases at old age (see ISO 7029, 1984). It is difficult to estimate from these data what proportion of people will be unable to use sound beacons. These "deaf" people could perhaps let themselves be herded by others with adequate hearing.

A limitation specific to beacons using natural language is insufficient mastery of that spoken language. Ours was a bi-lingual solution in which English and Dutch took turns. While increasing the proportion of the population that understands the beacons, this does not fully eliminate the limitation due to insufficient mastery of the language. Moreover, adding more languages increases the length of the total message (4 s for the current beacons) and beacons speaking (too) many languages may confuse the hearers.

Environmental noise is a third limitation on the effectiveness of sound beacons. The noise depends on the particular details of the environment such as engine noise in ships and the ventilation fans and traffic noises in tunnels. Ventilation fans alone, full power, can produce up to 100 dB(A). Moreover, the emergency itself may create additional noise. A mitigating condition for the tunnel situation is that motorists who have left their cars will probably follow the wall. Eventually, this will bring them in the vicinity of a sound beacon over an emergency exit. Because of proximity, the likelihood increases that they will hear the beacon.

Thermal imaging showed that vision-deprived test participants walk slower and with greater care than they would normally do. This prolongs their stay and their exposure to smoke. In the tunnel, we observed a walking speed above the one in the previous tunnel test with RW beacons (Boer and Withington, 2004). We ascribe this to more psychological confidence evoked by the self-explaining beacons of the current tunnel test, promoting walking speed for that reason. In a real disaster, motorists may have to walk a tunnel filled with untidily parked cars and, perhaps, debris. After collisions with obstacles, motorists will lose confidence and walk more slowly from then on. We prefer this psychological confidence interpretation over an interpretation in terms of visibility alone (such as given by Jin 1997).

Sound beacons will also be useful under conditions of good visibility. The continuous repetition "exit here" will help motorists to understand that they should leave their car and find refuge. The beacons can thus help to overcome the initial passivity of motorists surprised by a disaster (Boer 2002, 2003).

6. UPDATING THE EVACUATION MODEL

J. Fraser-Mitchell
BRE, UK

In the UPTUN project, CRISP is identified as a very promising model to handle scenarios involving tunnel emergencies. The CRISP model is a Monte-Carlo simulation for fire risk assessment. However it incorporates a detailed behaviour model, rather than something simpler which would run faster. The justification for this is that the risk assessment is based on fractional effective dose (FED) and accurate FED estimates require accurate exposure times. Therefore the behaviour model needs to predict where people will go, and how long they will spend in different areas (rooms) of the building. In a tunnel, the FED calculations would need to know how long people spent in different positions in the tunnel, relative to the fire location.

BRE's main input to this deliverable is to undertake research into human response and evacuation, and to develop a design methodology to assess human evacuation for different scenarios. A methodology to simulate people moving in groups and with luggage in situations with high and low visibility will be included here.

This chapter constitutes the development of a tunnel egress model to include the interaction of people with smoke and thermal hazards, the effects of luggage, and interaction within groups of people (as were studies in the chapter about evacuation behaviour).

A previous report for the FBE project reviewed egress behaviour and available analysis tools for predicting the movement of people following a tunnel fire. This chapter covers the further development of a generic human behaviour and evacuation model to enable simulation of tunnel emergencies. The idea of this work in UPTUN was to update the model based on the state-of-the-art, but also based on specific evacuation studies are were described in the chapter about evacuation behaviour).

Human behaviour is the most complex and difficult aspect of evacuation to simulate, yet is crucial to accurate results. This could be classified according to the type of algorithm employed (Gwynne, Galea, Owen, Lawrence & Filippidis (1998) but a somewhat simpler and more useful approach is to consider what types of behaviour are considered rather than the details of the calculation. The simplest level ("egress only") considers no other form of behaviour, apart from an abstract representation of "pre-movement" activities by a delay time for each occupant before they may start to move. The people may however be allowed some flexibility in exit choice.

The intermediate level ("fixed") covers models where the occupants may have a number of tasks to perform before they are allowed to commence evacuation. However these tasks are usually carried out in a deterministic sequence.

The highest level ("adaptive") also has occupants with a variety of tasks to perform, however the choice of task, and whether these are completed or replaced by alternative actions, is determined by the state of the environment, actions of other people encountered, etc. Adaptive behaviour models are potentially the most realistic, since the complexities of human behaviour are made explicit and amenable to users' control (rather than reflecting the original program developer's perceptions in a hard-wired algorithm).

Although each person's decision process is modelled separately, this does not preclude the option for co-operative or group behaviour. For example a person may have a task to rescue a dependant person; the dependant person may wait to be rescued. However when the rescuer meets the dependent, the task of both may change to "escape", and the movement process modified to keep the pair together.

6.1 An overview of the CRISP model

CRISP (Computation of Risk Indices by Simulation Procedures) is a Monte-Carlo model of entire fire scenarios (Fraser-Mitchell, 1994, 1996, 1997, 1998, 1999, 2000, 2001; Boyce, Fraser-Mitchell & Shields, 1998). The sub-models representing physical 'objects' include rooms, doors, windows, detectors and alarms, items of furniture, hot smoke layers, and people. The randomised aspects include starting conditions such as various windows and doors open or closed, the number, type and location of people within the building, the location of the fire and type of burning item.

The basic structure of CRISP is a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behaviour and movement. All the physical 'objects' are supervised by the Monte Carlo controller, making each one perform for each time step. The Monte Carlo controller also handles all the input and output, initialisation for each run, and starts each run automatically. Functions are included to generate random numbers from any distribution. The calculations for each run are carried out iteratively, with variable time intervals to ensure the program's efficiency, accuracy and stability.

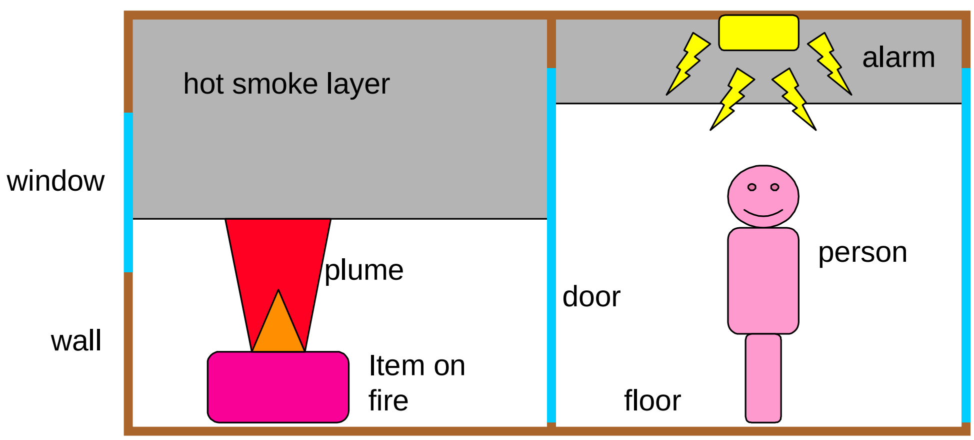


Figure 6.1: A schematic representation of the different object types within the CRISP model

Smoke moves between rooms by means of vent flows, driven by pressures arising from buoyancy differences. The geometry of the room determines how quickly a growing smoke layer will descend. Combustion products are transported between the various cold air and smoke layers by plumes and vent flows. Heat may also be lost by radiation and conduction through the walls of the compartment.

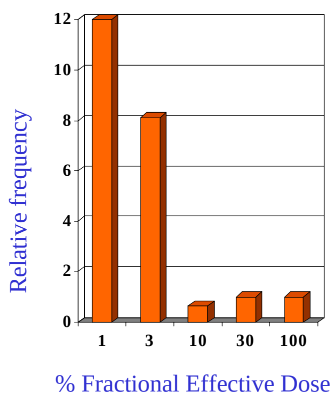
Vents are defined as doors and windows, or any other opening which smoke may move through. They may open or close during the simulation as people move through them. However, doors can be specified as self-closing. The traversal difficulty includes physical and psychological aspects.

People are assumed to adopt distinct behavioural roles, either naturally or due to training. Their behaviour can be described in terms of actions, which may be abandoned, and substituted by new ones, depending on the state of the environment. Rational decisions are made based on current knowledge (which may be limited and/or incorrect). People never 'panic' (in real life, 'panic' behaviour is actually extremely rare).

Movement of people through a building firstly requires a route to be planned through the network of rooms. The choice of route is influenced by the doors' transit difficulty (modified for the presence of smoke) and the distance. Within each room, movement to the next door on the route is directed by means of a 'contour map' of distance to go. This enables any obstacles to be avoided. Movement speed is affected by local crowd density. Deviations from the minimum distance path through a room may be made to avoid areas of high crowd density.

The model attempts to calculate 'pre-movement time' (rather than use an empirical distribution) in terms of the time delays associated with various actions performed by the occupants in response to the early fire cues. The occupants may perform a number of actions (eg. investigate, warn others) before actually starting to escape (thus the term 'pre-movement time' is not strictly accurate). If the occupant's 'pre-movement' actions do not actually require him to move, then all these actions can be lumped into a single delay in reacting to the alarm.

As the people move around, they are exposed to smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is assumed to be 'dead'. The risk is expressed simply in terms of the fraction of people originally present who end up 'dead', averaged over a sufficiently large Monte-Carlo sample.



- 400 Monte-Carlo runs
- 44702 people at risk
- 24 have FED = 1~2%
- 65 have FED = 3~9%
- 13 have FED = 10~29%
- 67 have FED = 30~99%
- 1 has FED > 100%
- risk of death = 2.2×10^{-5}
- risk of injury = 1.8×10^{-3}

Figure 6.2: Example of a typical risk calculation using CRISP

6.1.1 Tenability and DOD Concepts

Rooms are awarded a tenability rating of 0 ... 5 depending on the severity of conditions therein. Firstly, the tenability of each hot and cold gas layer is determined. A tenability of 0 is ambient, 5 is untenable for more than a few seconds. Values in Table 5-1 below partly come from the SFPE handbook (Purser, 1988) with interpolations where necessary. The overall tenability of the room is a weighted sum of the tenabilities of the hot and cold layers, with the weighting dependent on the position of the smoke/air interface relative to a nominal head height of 1.8m above the floor (Fraser-Mitchell, 1998, 1999).

In order for room conditions to alert a sitting person, an overall tenability of 1 or more is required, with weighting depending on the position of the interface relative to a height of 1.0m. Alerting a sleeping person requires a tenability of 2 or higher, with the weighting based on the position of the interface height relative to 0.8m above the floor. A sitting person may also be alerted by visible smoke (optical density greater than 0.01 m^{-1}) regardless of interface height.

The concept of tenability level is intimately connected with vent traversal difficulty (DOD). This may be physical or psychological, and affects people choosing a route from one room to another. The basic degree of difficulty (DOD) is physical. It may be increased if the tenability of the room on the far side is higher than the basic DOD. The DOD thus depends on the direction of travel. For buildings, the basic DOD for doors is 1, or 2 if rarely used or awkward. Windows have DOD = 3 (ground floor, awkward to use but not dangerous), DOD = 4 (first floor, only use if desperate), DOD = 5 (above first floor, impassable, due to certainty of injury or death). For tunnels, the tunnel portals could be given a DOD of 1 (the “familiar” exit), whereas emergency doors to cross-passages or refuges might be given a DOD of 2 or 3. If it is necessary to model the evacuation from train carriages in rail tunnels, the windows would probably have a DOD of 4, reflecting the extent of the drop to track level, and the likelihood that the windows will have to be smashed open before they can be used for egress.

Table 6-1: Factors Affecting Room Tenability Level

Tenability	heat flux (kW m^{-2})	opt. density (m^{-1})	temp. rise (^oC)	relative respiration rate
1	0.5	0.01	20	1.1
2	1.5	0.03	40	1.2
3	2.5	0.08	80	1.5
4	5.0	0.25	150	2.0
5	15.0	0.50	250	2.5

6.1.2 Decision Making

Having acquired information about their surroundings, the people must then decide how to respond. The basic element of behaviour is the 'action'. The allowable actions depend on the person's role ("workers" or "visitors" in an office scenario, maybe with some specialised roles, e.g. "warden", as well depending on the building). Each of the allowable actions has a number of conditions which, if true, cause the action to be terminated and another started. The model has scope for a random selection of new action from a list of options, but this capability has not been widely employed so far. The allowed actions, conditions and subsequent actions appropriate to each are stored in behaviour tables.

Decision making is recursive. A person will examine the conditions appropriate to their current action, and make a change if required to do so. The person then instantly assesses the conditions for the new action, and if appropriate changes that as well. This continues until an action is found that can be allowed to continue. The recursive nature of decision making means that complex behaviour can be specified using fairly compact tables.

Roles, actions and conditions must be devised to produce results consistent with observations of behaviour in real fires (Sime, Breaux & Canter, 1994; Kuipers, 1996) . The order of conditions is important, since they are tested in the order they are listed in the table. Conditions may not be mutually exclusive, and if two or more are applicable then the behaviour will branch according to the first one to yield a “true” result”.

Performing an action requires the person to move to a certain destination, followed by a time delay before the action is finished. These time delays are based on empirical observations, but may need to be supplemented with ‘reasonable guesses’ based on everyday experience. Where the time delay seems rather short, it should be noted that the overall time to complete an action will also include whatever time is required to move to the destination first. In particular, all actions with a delay of 0 seconds are associated with actions requiring movement. As soon as the destination has been reached a new action may be commenced. A time delay of 9999 seconds is effectively infinite, thus the action will not change unless a condition other than ‘complete’ is applicable. The short delay for the ‘trapped’ action requires comment. The behaviour rules are constructed in such a way that the program may go into an infinite loop, trying to find an acceptable action when a person was unable to move through smoke. The ‘trapped’ action was created to remedy this, by introducing short pauses in the decision-making process, and thus allow the program to continue.

The difficulty of the easiest route to the destination may not exceed 'allowed DOD', i.e. the person must not pass through a door or window whose traversal difficulty is higher than this value. In some cases 'allowed DOD' is not specified, the action will always be performed regardless of route difficulty. The 'urgency' of an action is used to determine whether the person performing the action will reassure others. An urgency value of 0 is 'normal', 1 is 'alert but in control', 2 is 'emergency!'.

An example of a behavioural "action" is given in Figure 6.3 below. Actions applicable to tunnel fire emergencies are discussed in more detail in a later section (6.3).

Current Action is		
FIGHT FIRE	Route destination	Fire Origin
	Allowed difficulty	2
	Urgency level	1
	Time to finish	5 seconds

Condition	New Action
Fire Out	Warn Household
Complete	Go To Water
No Route	Warn Household

Figure 6.3: Example of an 'action' – the components of the behaviour rules. All actions require movement to the destination (which may be the person's current room) followed by a time delay while the action is completed. The allowed difficulty refers to the severity of conditions (on a 0..5 scale, 5 is worst) that may be experienced before the action is abandoned. The urgency level determines how other people regard the person performing the action (0 = normal, 1= situation under control, 2 = time to get out!). On each time step of the model, conditions relevant to the current action are tested, and if one is true, the associated new action is attempted. For any condition, there may be any number of possible new actions, with different probabilities.

6.1.3 Interaction between people and smoke

The interaction between people and smoke is a crucial aspect of the model, since the presence of smoke is usually required to trigger people to start reacting (or trigger a detector, which then raises an alarm). Smoke may also provide an inhibiting effect on people attempting to complete various actions. Finally, the toxic effects of smoke are the basis of the risk calculation.

Despite this, there may be occasions when it is desired to turn the smoke production and movement subroutines off. It is possible to do this, and by adjustment of other parameters, "fool" the people into responding to a "virtual" fire.

Another possibility, which this project will explore in future, is to read in the smoke environment from a data file, at every time step of the model. The smoke environment would be calculated by a more sophisticated model, for example in tunnels the tunnel-specific zone model FASIT (Charters, Gray & McIntosh, 1994), or the tunnel-specific CFD model TUNFIRE. This would enable people to respond to the smoke, and suffer its toxic effects. The only feature it would not allow is for the actions of the people to affect the smoke movement (for example, by opening doors during the course of the simulated scenario).

The main technical issues concerning the import of pre-calculated smoke data are:

- ensuring consistency between the geometry of the CRISP model, and the model used to calculate the smoke movement. In CRISP, the zone model has two zones (hot and cold) for each "room". It is therefore necessary to ensure some sort of match-up between the CRISP "rooms" and the zones or control volumes used by the smoke model. For example, for the egress point of view it may be sufficient to represent a tunnel as just one long "room" or corridor. However this would ensure that there would be just one homogenous hot zone for the entire length of the tunnel – not a very realistic representation.

- ensuring consistency between the simulation time of the CRISP model, and the time associated with the smoke data values calculated by the smoke model, that are read in from the input data file. This would entail either using the data values closest in time to the current simulation time, or, if the smoke model had used relatively large time steps, interpolating the data in smoke way.

6.1.4 Effects of smoke toxicity

A number of different models (Purser, 1988, 1989; Purser & Berrill, 1983; Bryan, 1986; New ASTM toxic potency standard, 1995; Lieberman et al, 1994) have been proposed to account for the impact of various toxic gases on humans. Most are based on the concept of Fractional Effective Dose, where the dose rate is a function of various species concentrations, and is integrated over the duration of the exposure. When the accumulated FED becomes equal to 1.0, the exposed person is assumed to be unconscious / dead at that point. For design calculations, the dose rate is assumed to be dependent only on the environmental conditions, but in fact the variation in uptake rate between different people (eg. an elderly asthmatic, or a young fit adult) may vary by a factor of 10 or so (Zhao, 1998; Hartzell, 1998). The effect of FED<1.0 is on a person's performance is also not well understood.

The effect of toxic smoke in CRISP is expressed in terms of Fractional Effective Dose, FED (Purser, 1988). The equations developed by Purser have been recast into a suitable form, ie. rates of FED increase as a function of concentration by mass (K_x) of various combustion products. They have also been modified so that normal everyday ambient conditions do not cause an increase in FED.

$$\dot{F}_{CO} = 0.78 q K_{CO}^{1.04} \frac{\exp(2 + 12.5 K_{CO_2})}{7.1} + \dot{F}_{O_2}$$

(where q is a factor for respiration rate. q = 1 for most actions, but q = 0.34 if waiting, or not awake. The carbon dioxide concentration also affects the relative respiration rate)

$$\dot{F}_{O_2} = \frac{1}{60 \exp(8.13 - 49(0.23 - K_{O_2}))} - \frac{1}{60 \exp(8.13)}$$

$$\dot{F}_{CO_2} = \frac{1}{60 \exp(6.16 - 34 K_{CO_2})} - \frac{1}{60 \exp(6.16)}$$

As well as gases, the effect of exposure to heat has also been handled by a FED approach. Usually this is limited to convective heat transfer, when a person is immersed in / breathing hot smoke.

$$\dot{F}_{heat} = \frac{1}{60 \exp(5.18 - 0.027 \Delta\theta)} - \frac{1}{60 \exp(5.18)}$$

(where $\Delta\theta$ is the temperature rise above ambient).

F_{CO}, F_{CO_2} and F_{heat} are all integrated over the course of the simulation; when any of them equal 1.0 then the person becomes unconscious. The concentrations, K_{CO}, K_{CO_2} etc, are taken at the person's head height (modified for posture, if crawling).

Radiative heat transfer is handled by setting a threshold radiation flux, above which a region of the building becomes untenable due to rapid skin pain. However a FED approach for radiation has also been suggested (Clements & Gillespie, 1995), based on the time for skin pain to occur as a function of incident radiation flux. If for example the flux level is such that skin pain would occur in 50 seconds, then the FED rate is 1/50 =0.02 per second.

Table 6-2: Time to severe skin pain, for different radiant heat fluxes

Flux (kW/sq.m)	pain time (s)	FED per second (1/s)
25	1	1
15	2	0.5
11	3	0.33
8	5	0.2
4.7	10	0.1
3.5	15	0.067
2.8	20	0.05
2.5	25	0.04
2.3	30	0.033
2.15	40	0.025
2.07	50	0.02
2	60	0.0167
1.9	70	0.0143
1.8	80	0.0125
1.7	infinite	0

6.1.5 Employing CRISP as a stand-alone evacuation model

CRISP has a number of ‘switches’ which control how the program operates. One of these allows the model to run in evacuation mode, without simulating the fire or calculating toxic exposures. All the building occupants are assumed to be alerted at the start of the simulation. Once they have finished reacting, their full set of behavioural rules governs what they do next. A number of actions are only relevant in the presence of fire or smoke but can still be applicable if the fire is only implicit.

Clearly the standard metric for comparison of runs (risk of death) will not be applicable when there is no fire. However the model also calculates detailed statistics of the evacuation process. At the most basic level, there is the time required to clear a given proportion of the initial population (eg. 25%, 50%, 75%, 95%, 99%, 100%) from the building. It is also possible to determine when particular regions of the building have been cleared, and how long people from different starting points take to evacuate. At the finest level of detail, it is possible to monitor the flow rates at every doorway in the building.

Interpretation of the evacuation results may simply involve comparing the time for the building to become empty with some target time. Alternatively a fire model may be used to predict when regions of the building become untenable, and the evacuation results checked to confirm that nobody is inside or subsequently enters an untenable region. Where rooms are particularly large or complex in shape, a CFD model (eg. the BRE fire model JASMINE) is more likely to give accurate results for smoke flows, temperatures, etc, than CRISP's own internal fire model (because the zone model approximations may not be appropriate in a complex geometry).

The drawback to using an external fire model is that, as far as the evacuation process is concerned, there is no fire or smoke to respond to. However there are ways to implicitly include the fire in a rather abstract way (rather than the explicit representation employed in the full risk assessment mode). The transit 'degree of difficulty' for some doors can be set to a higher value than normal, to discourage or prohibit the entry of people into certain regions of the building (thus representing the presence of smoke). The behavioural rules followed by the people can also be modified to implicitly recognise the presence of a fire. For example, people in the vicinity of the fire may be given rules to enable them to react more quickly than those who are more distant. The more distant people could then react once warned by people who have already reacted, or they could remain inactive, waiting for a predetermined period (by which time a general alarm could be assumed to have been activated) before reacting.

6.2 Human Behaviour in Tunnel Fires

6.2.1 Different behavioural roles

Overall, behaviour patterns are not dissimilar to other building fires, although the tunnel fire environment may become severe more rapidly thus cutting down on some of the options.

As far as behaviour modelling for risk assessment purposes is concerned, only the more severe fires need to be considered. The probability of a severe fire, as opposed to any tunnel fire, can be estimated from statistics. The riskiest fires will be characterised by rapid fire growth, and rapid smoke spread. People will frequently be exposed to smoke at some stage, and when they are the visibility will be almost zero.

As in building fires, a person's role has a major effect on the behaviour they will exhibit. In tunnels, the roles can be generalised to include members of tunnel staff, members of the rescue and emergency services, other members of staff (eg. train or bus crew), and members of the public.

Tunnel control room staff form a special case, since they are not physically exposed to the fire and smoke hazard. Their actions should be reflected implicitly, for example in determining the length of the time delay before the emergency and rescue services are summoned, or in determining the time delay for other people to respond to an alarm (which would also depend on the type of alarm or warning message that was given).

The main effects of role on behaviour are that:

- Members of the public tend to wait for information, rather than investigate to seek it out. People in authority may investigate before undertaking positive action.
- Members of staff may search and warn/rescue others, whereas members of the public only warn/rescue on an impromptu basis if they discover someone in need. They may also assist others to cross obstacles (eg. to get off a train), and then escape independently when they have done this. Moving through train doors may be very time-consuming, as may opening the doors in the first place.
- Disabled people may either have helpers with them, or may receive impromptu assistance; in either case, their capabilities may not be quite so restricted (although the able-bodied helper may be slowed down for a time).

- Members of staff may attempt to fight the fire, members of the public are less likely to. However if only "serious" fires are being considered, it may be assumed that all attempts fail in these cases.
- Members of staff will attempt to control the evacuation by giving orders, directions, etc. Members of the public are less likely to do this, and more likely to be ignored if they try.
- Members of the public can only communicate face-to-face. Members of staff can communicate at a distance (eg. by radio amongst themselves, or by P.A. to members of the public) - as long as the system is still working.

Procedures in control rooms may break down under the stress of trying to manage the incident, and this should be reflected in the implicit behaviour of control room staff. Time delays may be much longer than anticipated if operations were carried out “by the book”, and in some cases actions may not be carried out at all.

Members of staff may also fail to behave as trained. Breathing apparatus may not be worn, thus preventing a member of staff from carrying out his required duties.

Group formation occurs, as in other building fires.

Drivers are extremely reluctant to abandon their vehicles - there may be a number of "good" reasons for this. People are also extremely reluctant to abandon their luggage, and will take it with them if possible when evacuating public transport. Luggage in private vehicles will be left behind when the vehicle is abandoned. (Small items may be taken, which would have no effect on the evacuation)

People will prefer to leave by the tunnel portal - the "familiar" route. Emergency exits will only be used if people are exposed to smoke, and even then may not be noticed. People will not be able to go past the fire, except perhaps at the earliest stages. If there are "authority figures" giving directions, these will involve moving away from the fire, rather than attempting to get past (to a nearer portal).

6.2.2 Action sequences for different behavioural roles

As mentioned above, the roles can be generalised to include members of tunnel staff, members of the rescue and emergency services, other members of staff (eg. train or bus crew), and members of the public. Examining the reports of actual tunnel fires in detail reveals slight differences in behaviour depending on whether the tunnel was road or rail.

The following tables list the behaviour sequences for different behavioural roles. Note that there need not necessarily be a 1:1 correspondence between a person’s occupation, and the behavioural role they will follow. For example, in the Taegu disaster [1] (http://times.hankooki.com/lpage/nation/200302/kt2003022418560411970.htm; http://www.cnn.com/2003/WORLD/asiapcf/east/02/23/skorea.subway.charges/; http://quickstart.clari.net/qs_se/webnews/wed/ak/Qskorea-fire-arrest.R6un_DFO.html; http://www.firetimes.com/subcontent.asp?FragID=7757; http://www.time.com/time/asia/magazine/article/0,13673,501030310-428127,00.html; http://quickstart.clari.net/qs_se/webnews/wed/at/Askorea-subway-fire.RCer_DFN.html; http://english.chosun.com/w21data/html/news/200302/200302190026.html), one of the train drivers was alleged to have abandoned the passengers to their fate. It is easier, when generating the model population, to define this driver as having a behaviour type of “passenger”, rather than trying to include the (conditional) probabilities of different actions within the behavioural rules for a given occupation type.

As far as tunnel staff are concerned, their behaviour either approximates to that of a train / coach driver, or a member of the rescue / emergency services.

In the tables below, the behavioural rules are laid out to a common pattern. The possible actions are listed in alphabetical order. In the next column, the conditions affecting the action are listed in the order that they are to be tested. If two or more conditions apply, the model will react to the first true condition. Each condition then leads to one or more possible new actions. If more than one action is possible, the choice will be made randomly according the relative probabilities.

In most cases, people will start in a waiting, un-alert state. Some passengers on trains may initially be asleep.

Behavioural rules have not been drawn up for control room staff. In the first place, they will (hopefully!) not be exposed to the fire directly. Secondly, their actions are likely to be extremely complex, and tunnel-specific. Therefore it is more appropriate to represent the actions of the control room staff in a more abstract manner, for example the time it takes other people to respond once the alarm is raised, than try to model all the actions of control room staff in individual detail.

Explanation of the actions and conditions can be found in section 4.3.

Finally, it should be noted that the behaviour rules listed below are generic in nature. For specific tunnels, with specific operational procedures, management structures, etc, the rules may be customised, extra roles defined, etc.

<u>Behaviour of train driver / staff / rail tunnel staff</u>

The core of the behaviour is an action sequence waiting – reacting – investigate – phone call – raise alarm – search own floor – choose exit – safe. There are interruptions to this sequence to direct people to the exits, or rescue people if required. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

The “search own floor” action is intended to limit the search to train carriages only. These will have a different floor height compared to the tunnel itself, enabling the model to recognise them.

The “choose exit” action is being used as a dummy action here, rather than in the manner originally envisaged when this action was first developed. The “alerted” condition should always apply at the moment this action starts, thus the effect is to force a choice between “escape” or “standard exit”. These two actions could have been given as a pair of options, wherever there is currently a “choose exit” action. However, the advantage of the approach adopted here is that the probabilities can be changed in just one place in the data file, minimizing the chance of making errors.

Table 6-3: Behaviour of train driver / staff / rail tunnel staff

ACTION		CONDITION		NEW ACTION(S)	
choose_exit	o	alerted	------- ----->	escape	50%
			'---->	standard_exit	50%
direct_crowd	o	complete	------- ----->	direct_crowd	
	o	no_route	------- ----->	choose_exit	
escape	o	complete	------- ----->	safe	
	o	no_route	------- ----->	make_refuge	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	direct_crowd	
investigate	o	complete	------- ----->	phone_call	
	o	no_route	------- ----->	phone_call	
	o	PA_warning	------- ----->	choose_exit	50%
			'---->	search_own_floor	50%
	o	senior_alerted	------- ----->	phone_call	
	o	seniors_away	------- ----->	raise_alarm	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
make_refuge	o	complete	------- ----->	make_refuge	90%
			'---->	choose_exit	10%
	o	no_route	------- ----->	trapped	
phone_call	o	PA_warning	------- ----->	choose_exit	
	o	complete	------- ----->	raise_alarm	
	o	no_route	------- ----->	raise_alarm	
	o	tgt_alerted	------- ----->	phone_call	
raise_alarm	o	PA_warning	------- ----->	choose_exit	50%
			'---->	search_own_floor	50%
	o	complete	------- ----->	choose_exit	50%
			'---->	search_own_floor	50%
	o	no_route	------- ----->	choose_exit	
reacting	o	complete	------- ----->	investigate	
	o	no_route	------- ----->	phone_call	

Table 6-4: Behaviour of train driver / staff / rail tunnel staff (continued)

ACTION		CONDITION		NEW ACTION(S)	
rescue	o	complete	------- ----->	choose_exit	
	o	no_route	------- ----->	choose_exit	
safe	o	complete	------- ----->	safe	98%
			'---->	rescue	2%
search_own_floor	o	complete	------- ----->	search_own_floor	80%
			'---->	choose_exit	20%
	o	no_route	------- ----->	choose_exit	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	direct_crowd	
standard_exit	o	complete	------- ----->	safe	
	o	no_route	------- ----->	escape	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	direct_crowd	
trapped	o	complete	------- ----->	choose_exit	
unconscious	o	complete	------- ----->	unconscious	
waiting	o	complete	------- ----->	waiting	
	o	alerted	------- ----->	reacting	

Behaviour of coach driver / road tunnel staff

The core of the behaviour is an action sequence waiting – reacting – direct people to exits – choose exit – safe. There are interruptions to this sequence to rescue people if required. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

The “direct crowd” action is intended to apply to the coach driver’s passengers only. This action is therefore only performed for the “room” representing the coach interior. After all passengers have been directed, the driver will escape.

Table 6-5: Behaviour of coach driver / road tunnel staff

ACTION		CONDITION		NEW ACTION(S)	
choose_exit	o	alerted	------- ----->	escape	50%
			'---->	standard_exit	50%
direct_crowd	o	complete	------- ----->	direct_crowd	
	o	no_route	------- ----->	choose_exit	
escape	o	complete	------- ----->	safe	
	o	no_route	------- ----->	make_refuge	
	o	tgt_to_rescue	------- ----->	rescue	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
make_refuge	o	complete	------- ----->	make_refuge	90%
			'---->	choose_exit	10%
	o	no_route	------- ----->	trapped	
reacting	o	complete	------- ----->	direct_crowd	
	o	no_route	------- ----->	choose_exit	
rescue	o	complete	------- ----->	choose_exit	
	o	no_route	------- ----->	choose_exit	
safe	o	complete	------- ----->	safe	
standard_exit	o	complete	------- ----->	safe	
	o	no_route	------- ----->	escape	
	o	tgt_to_rescue	------- ----->	rescue	
trapped	o	complete	------- ----->	choose_exit	
unconscious	o	complete	------- ----->	unconscious	
waiting	o	complete	------- ----->	waiting	
	o	alerted	------- ----->	reacting	

<u>Behaviour of rescue / emergency services</u>

The core of the behaviour is an action sequence waiting – reacting – investigate – rescue – fight fire – escape – safe. There are interruptions to this sequence to issue directions to people if required. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

It is implicitly assumed in this behaviour sequence that it applies to fire brigade personnel. Other rescue services would skip the fire-fighting behaviour. Tunnel staff trying to act as rescue services could be required to alternate “fight fire” with an action “go to water”. This action can cover use of extinguishers, hose reels, etc. These need not be explicitly simulated by the model; instead, the provision of first-aid fire fighting aids could be reflected in the length of the time delay imposed by the “go to water” action. Not only would this action slow tunnel staff down, by setting the allowed DOD for the latter action to be less than that for “fight fire”, it would lead to the fire-fighting being abandoned at an earlier stage than if it was properly trained and equipped firemen tackling the fire.

Another point to note about this behaviour is that there is no “choose exit” option, instead there is only “escape”. This is because the people using this behaviour are assumed to be familiar with the tunnel, thus more prepared to use the side emergency doors rather than attempting to reach the tunnel portals.

Table 6-6: Behaviour of rescue / emergency services

ACTION		CONDITION		NEW ACTION(S)	
direct_crowd	o	complete	------- ----->	direct_crowd	
	o	no_route	------- ----->	investigate	
escape	o	complete	------- ----->	safe	
	o	no_route	------- ----->	make_refuge	
	o	tgt_to_rescue	------- ----->	rescue	
fight_fire	o	complete	------- ----->	fight_fire	
	o	no_route	------- ----->	escape	
investigate	o	seen_fire	------- ----->	rescue	
	o	complete	------- ----->	rescue	
	o	no_route	------- ----->	rescue	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	direct_crowd	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
make_refuge	o	complete	------- ----->	make_refuge	90%
			'---->	investigate	10%
	o	no_route	------- ----->	trapped	
reacting	o	complete	------- ----->	investigate	
	o	no_route	------- ----->	investigate	
rescue	o	complete	------- ----->	escape	
	o	no_route	------- ----->	fight_fire	
safe	o	complete	------- ----->	investigate	
trapped	o	complete	------- ----->	investigate	
unconscious	o	complete	------- ----->	unconscious	
waiting	o	complete	------- ----->	waiting	
	o	alerted	------- ----->	reacting	

<u>Behaviour of public, rail tunnels</u>

The core of the behaviour is an action sequence asleep – wake up – waiting – reacting – complete work – rejoin family – rescue family – choose exit – safe. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

The action “complete work” was originally developed for office fire scenarios. It is included here as an alternative waiting action for the majority of the people who choose to ignore the initial fire cues. It will require a higher level / less ambiguous cue (for example, deteriorating conditions, other people leaving, or a PA warning) for people to respond.

The action “order to leave” was also originally developed for office scenarios, to represent the effect of floor wardens who were searching the building and telling people who were slow to leave that it was time to do so. In the tunnel context its’ use is slightly different, since it is intended to simulate the effect of seeing other people leaving the tunnel acting as a cue. People who order others to leave do not actually stop to tell others to get out, hence the time delay for this action is zero. The action “respond to order” is then used to determine how people react to the cue of seeing others leaving, whether by leaving themselves (“rejoin family – rescue family – choose exit – safe”), or by ignoring the cue (“ignore order”).

The action “ignore order” is another generic waiting action, for people who disregard the cue of other people exiting the tunnel.

People will actively seek out other members of a pre-existing group (“rescue family”), but will only assist other people in need (not previously affiliated) if these are encountered during the egress.

Table 6-7: Behaviour of public, rail tunnels

ACTION		**CONDITION**		**NEW ACTION(S)**	
asleep	o	complete	------- ----->	asleep	
	o	alerted	------- ----->	wake_up	
	o	no_route	------- ----->	wake_up	
choose_exit	o	alerted	------- ----->	escape	50%
			'---->	standard_exit	50%
complete_work	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
escape	o	complete	------- ----->	safe	
	o	no_route	------- ----->	make_refuge	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	order_to_leave	
ignore_order	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
make_refuge	o	complete	------- ----->	make_refuge	90%
			'---->	choose_exit	10%
	o	no_route	------- ----->	trapped	
order_to_leave	o	complete	------- ----->	previous	
	o	no_route	------- ----->	choose_exit	
reacting	o	complete	------- ----->	rejoin_family	5%
			'---->	complete_work	95%
	o	no_route	------- ----->	choose_exit	
rejoin_family	o	complete	------- ----->	rescue_family	
	o	no_route	------- ----->	choose_exit	
rescue	o	complete	------- ----->	choose_exit	
	o	no_route	------- ----->	choose_exit	

Table 6-8: Behaviour of public, rail tunnels (continued)

ACTION		CONDITION		NEW ACTION(S)	
rescue_family	o	complete	------- ----->	choose_exit	
	o	no_route	------- ----->	choose_exit	
respond_to_order	o	complete	------- ----->	rejoin_family	10%
			'---->	ignore_order	90%
	o	no_route	------- ----->	rejoin_family	
safe	o	complete	------- ----->	rescue_family	
standard_exit	o	complete	------- ----->	safe	
	o	no_route	------- ----->	escape	
	o	tgt_to_rescue	------- ----->	rescue	
	o	tgt_to_order	------- ----->	order_to_leave	
trapped	o	complete	------- ----->	choose_exit	
unconscious	o	complete	------- ----->	unconscious	
waiting	o	complete	------- ----->	waiting	
	o	alerted	------- ----->	reacting	
wake_up	o	complete	------- ----->	reacting	

<u>Behaviour of public, road tunnels</u>

The behaviour of members of the public in road tunnels is very similar to that in rail tunnels, with the differences that road users are less likely to be asleep initially, and also that they do not tend to rescue others (perhaps this is simply because they are less likely to encounter them, in the less confined environment of a road tunnel, rather than any lower levels of altruism).

The core of the behaviour is an action sequence waiting – reacting – complete work – rejoin family – rescue family – choose exit – safe. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

The action “complete work” was originally developed for office fire scenarios. It is included here as an alternative waiting action for the majority of the people who choose to ignore the initial fire cues. It will require a higher level / less ambiguous cue (for example, deteriorating conditions, other people leaving, or a PA warning) for people to respond.

The action “order to leave” was also originally developed for office scenarios, to represent the effect of floor wardens who were searching the building and telling people who were slow to leave that it was time to do so. In the tunnel context its’ use is slightly different, since it is intended to simulate the effect of seeing other people leaving the tunnel acting as a cue. People who order others to leave do not actually stop to tell others to get out, hence the time delay for this action is zero. The action “respond to order” is then used to determine how people react to the cue of seeing others leaving, whether by leaving themselves (“rejoin family – rescue family – choose exit – safe”), or by ignoring the cue (“ignore order”).

The action “ignore order” is another generic waiting action, for people who disregard the cue of other people exiting the tunnel.

People will actively seek out other members of a pre-existing group (“rescue family”), but will only assist other people in need (not previously affiliated) if these are encountered during the egress.

The percentages for the possible actions following “respond to order” have been taken from the results of an experiment performed in the Netherlands (Boer, Winer & Noren, 2004). In this experiment, 18% of drivers responded after seeing “smoke” from a halted lorry, but the remaining 82% did not leave their cars until a PA message told them to exit the tunnel. In the unpublished car simulation tests carried out for Eurotunnel, people were presented with cosmetic smoke from a car at the front of the wagon, while seated in their cars. People in the cars behind the "fire" were observed to sit and watch developments, in some cases they just closed their windows to keep the smoke out of their own car. They only left their car and the wagon when they heard an instruction to do so, or saw others leaving (Canter, Donald & Chalk, 1995).

Witnesses from the Tauern tunnel reported how some drivers refused to leave their cars, despite the chaos around them (http://www.landroverclub.net/Club/HTML/Travel_TauerTunnel.htm; The Observer newspaper, 30th May 1999). In the St Gotthard tunnel, some drivers stayed in their vehicles and tried to telephone for help (http://www.cnn.com/2001/WORLD/europe/12/21/tunnel.reopen/?related).

In cars, it is likely that passengers would take the lead from the actions of the driver. They would therefore do nothing until the driver had responded decisively (“rejoin family – rescue family – choose exit – safe”), whereupon they would respond decisively too.

In the behaviour listed in the Table 5-9, a single driver has a 95% chance not to react at once, whereas in a car with (n-1) passengers as well, the chance that none of them react at once is 0.95^n. Once the first has reacted decisively, the “choose exit” behaviour would be interrupted to provide a cue for others to leave – but 82% of the time, another person would ignore this cue.

A better way to represent what should happen (all people in a car going at the same time) may be to have separate behavioural roles for the driver and the passengers. The passenger behaviour would be almost identical to that given in Table 5-9, except that reacting would only be followed by “complete work” and “respond to order” would only be followed by “ignore order”. However, “ignore order” would have an extra condition, for the order originating from a member of the same “family”, that causes the “rejoin family” … etc sequence to start up.

The report on the Netherlands experiment (Boer, Winer & Norem, 2004) also suggested the existence of “herding” effects, after the announcement to leave was made on the PA system. Of those people who had not responded prior to this, there was a delay until the first person left their car, whereupon the others followed rapidly behind them. It was also noted in some of the tests, where significant numbers of people left before the PA announcement, they responded shortly after the first of their number had started to leave.

Accounts of the road tunnel fires make it clear just how attached motorists are to their vehicles. It is probable that the main reason for this is that they do not want to abandon their journey. Also, given that the “familiar” exit is the tunnel portal, the only practical way to reach this may be by vehicle. Numerous accounts exist of drivers attempting to manoeuvre their vehicles out of a tunnel during a fire ([1] http://www.landroverclub.net/Club/HTML/Travel_TauerTunnel.htm; The Observer newspaper, 30th May 1999; http://fpeng.peopledaily.com.cn/200110/25/eng20011025_83124.html; http://www.guardian.co.uk/international/story/0,3604,581224,00.html; http://archives.tcm.ie/breakingnews/2001/10/25/story27708.asp; http://edition.cnn.com/2001/WORLD/europe/10/25/switzerland.tunnel/; Gray & Varkevisser (1995)

The vehicle may also act as a temporary refuge, with the windows closed to keep out smoke.

The CRISP model currently does not have the facility to include moving vehicles. However stationary vehicles could be included, as obstructions to movement, or as “rooms” within the tunnel that could be used as temporary refuges.

There is also the inconvenience of being without transport, should drivers and passengers leave on foot while the car or lorry is left to be destroyed in the fire. Although the vehicle will (probably) be insured, all the extra effort involved in making a claim and receiving a satisfactory settlement will encourage the (private) motorist to save his vehicle if at all possible.

Finally, people may be concerned about theft, should they leave their vehicle unattended. Motorists are therefore inclined to stay in their cars, and if asked to leave them unlocked, are unwilling to do so (Rhodes & Wong, 2001). In the Netherlands experiment, Boer, Winer & Noren, 2004) about 25% of motorists stopped to lock their cars. However this action has not been included as the effect is likely to be negligible.

Table 6-9: Behaviour of public, road tunnels

ACTION		CONDITION		NEW ACTION(S)	
choose_exit	o	alerted	------- ----->	escape	50%
			'---->	standard_exit	50%
complete_work	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
escape	o	complete	------- ----->	safe	
	o	no_route	------- ----->	make_refuge	
	o	tgt_to_order	------- ----->	order_to_leave	
ignore_order	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
make_refuge	o	complete	------- ----->	make_refuge	90%
			'---->	choose_exit	10%
	o	no_route	------- ----->	trapped	
order_to_leave	o	complete	------- ----->	previous	
	o	no_route	------- ----->	choose_exit	
reacting	o	complete	------- ----->	rejoin_family	5%
			'---->	complete_work	95%
	o	no_route	------- ----->	choose_exit	
rejoin_family	o	complete	------- ----->	rescue_family	
	o	no_route	------- ----->	choose_exit	
rescue_family	o	complete	------- ----->	choose_exit	
	o	no_route	------- ----->	choose_exit	
respond_to_order	o	complete	------- ----->	rejoin_family	18%
			'---->	ignore_order	82%
	o	no_route	------- ----->	rejoin_family	
safe	o	complete	------- ----->	rescue_family	

Table 6-9: Behaviour of public, road tunnels (continued)

ACTION		CONDITION		NEW ACTION(S)
standard_exit	o	complete	------- ----->	safe
	o	no_route	------- ----->	escape
	o	tgt_to_order	------- ----->	order_to_leave
trapped	o	complete	------- ----->	choose_exit
unconscious	o	complete	------- ----->	unconscious
waiting	o	complete	------- ----->	waiting
	o	alerted	------- ----->	reacting

Behaviour of dependent members of the public

The behaviour of dependent members of the public is very similar to that in of other members of the public, with the differences that they do not escape under their own initiative, but require assistance from others.

The core of the behaviour is an action sequence asleep – wake up – waiting – reacting – complete work – rejoin family – await rescue. Actions such as leave room, unconscious or trapped are required for all people regardless of role.

Sleeping and waking up would only apply to dependents in rail tunnels.

If the dependent was immobile, the "rejoin family" would never be completed, unless the dependent was initially in close proximity to the "head" of the "family".

Dependents become safe after successive leave room actions, or (more likely) after someone has rescued and carried them outside. They never escape (other than "accidentally" by successive "leave room" actions), and never attempt to make refuges for themselves.

Table 6-10: Behaviour of dependent members of the public

ACTION		CONDITION		NEW ACTION(S)	
asleep	o	complete	------- ----->	asleep	
	o	alerted	------- ----->	wake_up	
	o	no_route	------- ----->	wake_up	
await_rescue	o	complete	------- ----->	await_rescue	
	o	no_route	------- ----->	leave_room	
complete_work	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
ignore_order	o	complete	------- ----->	rejoin_family	
	o	no_route	------- ----->	rejoin_family	
	o	PA_warning	------- ----->	rejoin_family	
leave_room	o	complete	------- ----->	previous	
	o	cannot_leave	------- ----->	trapped	
reacting	o	complete	------- ----->	rejoin_family	5%
			'---->	complete_work	95%
	o	no_route	------- ----->	rejoin_family	
rejoin_family	o	complete	------- ----->	await_rescue	
	o	no_route	------- ----->	await_rescue	
respond_to_order	o	complete	------- ----->	rejoin_family	5%
			'---->	ignore_order	95%
	o	no_route	------- ----->	rejoin_family	
safe	o	complete	------- ----->	safe	
trapped	o	complete	------- ----->	rejoin_family	
unconscious	o	complete	------- ----->	unconscious	
waiting	o	complete	------- ----->	waiting	
	o	alerted	------- ----->	reacting	
wake_up	o	complete	------- ----->	reacting	

6.2.3 Different actions performed during tunnel emergencies

This section describes the implementation, within CRISP, of the various actions and conditions contained within the behaviour sequences above.

<u>Actions, the constituent units of behaviour</u>

asleep

The initial action of somebody who is sleeping. Sleepers have less awareness of their surroundings (obviously they can't see anything !) and are more difficult to alert than people who are awake. Destination = current room. When the action is complete, the action should either become 'wake_up' or 'asleep'. When the 'alerted' condition is true (see below) the action should become 'wake_up'.

await_rescue

Distinguished from the initial waiting state (qv) to allow different conditions to be applied, eg. the person doing this action is expected to be alert, so do not want to terminate the action on an 'alerted' condition (see below). Destination = current room. This action could either continue indefinitely, or you could use an 'impatient' condition to trigger something different.

choose_exit

An attempt to simulate the non-optimal choice of egress path made by a person who is unfamiliar with the building geometry. Successive ‘choose_exit’ actions will gradually lead a person towards the outside. The exit choice determines the destination room; when the action is complete the person will have just crossed the threshold into the destination room.

The exits from a room are assigned scores on the basis of the overall difficulty (DOD) and distance of a route to the outside that starts by going through the chosen vent. If there is no DOD-distance trade-off in calculating the score (i.e. switch(13) = 0) then the score for exit i is just given by

$$S_i = 10000.DOD + dist$$

On the other hand if there is trade-off, the score is calculated as

$$S_i = dist.f^{DOD-1}$$

provided the overall DOD for the route is not more than 2; if DOD is 3 or more, use the first expression for S_i. The exit choice factor f is defined in the global data file.

The next stage is to convert the scores, to calculate the probabilities of exit choice. Let S_0 be the smallest value among the S_i’s, and define

$$S_i' = S_i - S_0 + 0.01$$

where the constant factors of 0.01 have been included to guard against division by zero errors when calculating the probabilities. The relative probability of exit choice is defined as

$$p_i = S_0' / S_i'$$

One of the exits from the room is chosen at random according to the relative probability. As can be seen from the above expressions, doors that yield shorter routes to the outside, or lower DOD, are more likely to be chosen. For example, given a choice between two doors, of equal DOD but one having a distance to the outside which is half that of the other, the probabilities of choice will be 0.66 and 0.33 respectively.

complete_work

Initially developed for office occupancies, this is another generic waiting action, so can be used in any building. Destination = current room.

direct_crowd

This is based closely on local_warn (see below). The main difference is that, rather than seeking out room mates who aren't alerted yet, the person p looks for people whose action is not "escape". Also, there is no check that a room-mate is going to re-direct the whole room.

Note that finish_action will need to set the target person(s) action to "escape" otherwise an infinite loop will be the result!

escape

Person makes their way to the outside, using the default route if possible, otherwise the optimum route. (If the person has previously succeeded in rescuing somebody, that person will be carried along too). This action should be used by people who are familiar with the building geometry, due to the way the model selects the route.

fight_fire

Person makes their way to the room of fire origin, and then engages in manual fire-fighting. When the action is completed the fire is assumed to have been extinguished. The person should previously have completed a 'go_to_water' action to provide themselves with the means to extinguish the fire.

go_to_water

Fire fighting is a two-stage process, the first stage is to collect some means of tackling the fire. The destination of this action is a room with type 'kitchen' or 'bathroom' (in a domestic occupancy, both of these would have a ready supply of water). Other means of extinguishing, eg hand-held extinguishers, have not yet been included in the model.

ignore_order

Destination = current room. This is a waiting action, but should have urgency = 2 so that a person who has given an order_to_leave does not attempt to order this person again.

investigate

Destination = room of fire origin

leave_room

This action is started automatically, regardless of what the person might be doing, if the tenability level of the room exceeds a value of 4 (or the allowed DOD of the current action, if higher). NB. the maximum value the tenability level can have is 5 (worst). The destination is the nearest of the adjoining rooms with lower tenability level than the current room. If none of the surrounding rooms has lower tenability (or the doors linking the rooms have a DOD of 5 or more) then the 'no_route' condition will be true and the action should change to 'trapped'. On the other hand if the action is successfully completed, the person will usually want to revert to their previous action.

local_warn

Not a perfect algorithm, but enables very large spaces to be warned more realistically rather than everybody simultaneously as a consequence of "warn household". It will only look at people in the same room as person p; wayfound will be false once all these have been alerted. The optimum targ_man will be the one having the minimum cartesian distance from person p, ignoring obstacles at the present stage of development.

The call to check_mates(p,tgt_alerted,result) is to see if the local_warn action is about to be overruled by a more senior person with a WARN_HOUSEHOLD action (which will get everbody in the room). If two people have LOCAL_WARN actions for the same man, they'll both carry on until the first of them has finished.

order_to_leave

Destination = current room. When complete, anybody in the room will be required to stop what they are doing, and respond to the emergency, unless they are already doing an action with urgency = 2. IMPORTANT NOTE. Due to a particularly nasty piece of coding, after the action 'order_to_leave' has been completed, any recipients of the order will be required to 'raise_alarm'. (See above. This is a hardwired fudge that has not got around to being corrected. At the time this gave a reasonable sequence of actions). However there is an easy way to get the people ordered to leave to do any desired action - just regard the 'raise_alarm' as a dummy action, and test only for the condition 'alerted'. As this condition will always be true of someone ordered to leave, they can then start a new action immediately.

phone_call

This action just selects as targ_man the most senior unalert person of same role as caller. It is assumed that the caller is in the presence of a phone (or radio). It is also assumed that the recipient of the call has the appropriate equipment to hand as well. When the action is complete, the recipient of the call is alerted.

previous

In many cases an action may be regarded as an interruption to a previous activity, rather than a complete change of strategy. For example, suppose a warden is searching a building. He comes across somebody who is not reacting to the alarm, so interrupts the search to order them to leave. He would then wish to resume the search rather than abandon it half-way through the building. The 'previous' action will be the most recent successfully-started one that is different to the current action. Sometimes a new action will be started that is the same as the current action. This may be simply to keep the current action going indefinitely, or it may entail a change of destination).

Note that the way the behaviour tables work, CRISP may go though several unsuccessful actions before finding one that is OK. Example: suppose that after reacting, a man would normally go to investigate the fire, and when that is complete, then proceed to warn the household. However, by the time he has finished reacting, the room tenabilities may be such that he is unable to investigate, although still able to warn. If, while he was doing the warning action, a condition arose that required him to perform the 'previous' action, this would be reacting, and not 'investigate' because the latter was never successfully started ('no_route' condition stops it).

raise_alarm

Destination = the nearest room containing a 'breakglass' detector (or the room with the least difficult route). When the action is complete, the alarm is activated. IMPORTANT NOTE. Due to a particularly nasty piece of coding, after the action 'order_to_leave' (see below) has been completed, any recipients of the order will be required to 'raise_alarm'. (This is a hardwired fudge that has not got around to being corrected. At the time this gave a reasonable sequence of actions). However there is an easy way to get the people ordered to leave to do any desired action - just regard the 'raise_alarm' as a dummy action, and test only for the condition 'alerted'. As this condition will always be true of someone ordered to leave, they can then start a new action immediately.

reacting

Used to introduce a short delay between a person first being alerted, and being ready to respond (eg. to realise the bells aren't the weekly fire alarm test). Destination = current room. It may be desired to simplify the human behaviour by lumping all the 'pre-movement' actions into a single delay period, before the person then evacuates. In this case it makes sense to just extend the delay period (see action data files) for this action, and then 'escape' or 'choose_exit' when reacting is complete.

rejoin_family

Not intended to be a perfect algorithm at this stage, merely a stop-gap solution. The destination will be the current room of the person’s family head. Odds are, the family head will also be alert and will have started escaping or whatever. The point is not so much for the family to actually all join up, as for contra-flow situations to be set up which will impede the movement of the escapers. If the condition 'tgt_moved' is true, the man could be given a behaviour rule to try again to find the family head, or to simply give up and escape on his own.

rescue

The destination is the room containing the dependent or unconscious person with the lowest seniority still in the building. However if the current room contains a dependent or unconscious person then the destination will be the current room. When the action is complete the person being rescued will have their 'assisted' status flag set. The person doing the rescuing should then change action to one that leads outside, ie 'escape' or 'choose_exit' (qv). The assisted person will be carried along by the helper.

rescue_family

This action is almost identical with the standard "rescue" action except that the potential men to be rescued are restricted to the person's family members only. However this does not run through family in reverse order of seniority as "rescue" does (using peckorder), but instead uses reverse order of person creation. This is unlikely to have a huge significance. When the action is complete, not only is the man being rescued given a status of ‘assisted’, but all other members of the family in the same room are given orders to leave, if the urgency level if their current action is less than 2

respons_to_order

This is a waiting action of short duration, after which people can respond to an order_to_leave action of another person.

safe

The destination is the current room. Usually the action will only be started if the person has reached the outside (eg. on the completion of 'escape', or on the 'outside' condition if the action is 'choose_exit'). Once the time delay associated with the 'safe' action has elapsed, the person gets the chance to choose another action - so they may re-enter the building, eg if it still contains dependents who will need to be rescued. On the other hand, if the only new action after 'safe' is complete is to restart the 'safe' action, then the program can just skip over this person for the rest of the simulation (because they aren't going to do anything else), thus speeding the program up.

search_fire_floor

This action is very similar to ‘search_rooms’, except that there is an additional restriction that the destination room must be on the same floor as the fire room (i.e. their floor z-co-ordinates are within 0.5m of one-another).

search_own_floor

This action is very similar to ‘search_rooms’, except that there is an additional restriction that the destination room must be on the same floor as the person’s current room (i.e. their floor z-co-ordinates are within 0.5m of one-another).

search_rooms

Destination = nearest room that has not already been searched (or the room with the least difficult route). Normally in a building of any size there would be more than one person tasked with this role. Some simplifying assumptions have been made to get a reasonable approximation of a cooperative search effort: (a) every person is aware of which rooms have already been searched; (b) every person is aware of which room is going to be searched by another person of the same behavioural role as themselves. In the course of their search, if people are found who should be warned or rescued, then the search action should revert to the appropriate new action, and then that new action back to 'previous' when complete.

standard_exit

This is very similar to start_escape, but sets switches to force the use of {DOD, then dist} route scoring (see “choose_exit”). This will ensure the lowest-DOD route to the outside will be chosen - it's up to the program user to arrange the geometry file so that the "standard" exit(s) do indeed have lowest DOD. Switches are reset after the route is found, so as not to affect other aspects of the program operation.

trapped

This action introduces a short delay. When it is complete, the action should usually revert to whatever the person was doing previously. The reason this action was introduced was to avoid infinite loops in the human behaviour. If room conditions become very bad, it may no longer be possible to find satisfactory routes for any action. (The 'no_route' condition would always be true). This action ensures that the decision process is always able to end up with an action that can be performed. After the action is complete, if conditions in the building have improved, it may be possible to restart the previous action. Otherwise, another 'trapped' action will ensue. Destination = current room.

unconscious

This occurs automatically when a person's FED exceeds 100%. Destination = current room. When the action is complete (give it a huge time delay), another 'unconscious' action should commence.

waiting

This is the initial action performed by someone who is awake. Destination = current room. A reassured person will also automatically revert to a waiting action (however they will have a flag set to indicate they have been reassured, rather than not alerted yet, so can behave differently when re-alerted than when alerted for the first time).

(The program may also cause a person to revert to a waiting action if the action they were requested to do is not actually defined in their behaviour tables. Strictly speaking, I suppose the program should just crash at this point instead and force you to fix the error. However the program does print a warning to the console telling you what's going on)

wake_up

This action introduces a delay before a person has woken up, got out of bed, got dressed, etc. When complete, the action should become 'waiting' (which will probably then be changed immediately as a result of the 'alerted' condition being true). Destination = current room

warn_household

Destination = room containing the most senior man who is not already alerted. The destination may be changed to the current room if this contains people who are not alert. When the action is complete, everyone in the room (not just the target man for the action) is alerted.

warn_neighbour

Destination = current room. Usually this action will be restricted to people who are already outside, after their 'safe' action is complete. The idea is to tie someone up with a long time delay, so they are not available to re-enter the building eg. to rescue others still inside.

<u>Conditions which affect behaviour</u>

The conditions are true, for the person whose behaviour is being calculated, in the following circumstances as described below.

alarm_to_raise

The person’s current room contains a detector of type ‘breakglass’, and no alarms are audible (attenuated sound > 20dBA) from the person’s current room

alerted

The person is alert (i.e. has seen smoke of sufficient density, or has heard an alarm, or has been warned by someone else)

cannot_leave

The person is attempting a ‘leave_room’ action, but no suitable destination can be found.

complete

The person’s current action is complete, as the necessary waiting period at the end of any movement has now elapsed

fire_out

The person is currently in the room of fire origin, and the fire heat output rate is currently less than 0.01kW

has_reacted

The person has previously completed a ‘reacting’ action.

impatient

The person is currently moving (or attempting to move), rather than waiting, queuing to cross a threshold, or opening or closing a door. The condition will be true if a random number, U(0,1), produced by the program, satisfies the following inequality:

$$U(0,1) \leq 0.02dt'$$

where dt’ is the amount of the time step remaining. The effect of this inequality is that the times taken for moving people to become impatient follow an Exponential distribution, with a mean of approximately 50 seconds.

no_route

If the tenability level of any room on the route to the destination is known to be higher than the allowed DOD for the person’s current action, the person will restart their current action to try to find an alternative route. If this fails to find a route, the condition will be true.

The condition may also be true if a suitable destination does not exist, for example ‘warn_household’ will give a true result for ‘no route’ if everybody in the building is already alert.

outdoors

The person’s current ‘room’ is ‘outside’, i.e. the room ID is zero.

PA_warning

No alarms are audible (attenuated sound > 20dBA) from the person’s current room

realerted

The person had previously been reassured (changing their action to ‘waiting’ but with a status flag ‘was_alert’ set true), and has now become alert again due to worsening conditions.

seen_fire

The person had previously been in the room of fire origin, but is not there now.

senior_alerted

Somebody in the same room, who has greater seniority than the person checking, is alert.

seniors_away

The person checking is the most senior in the whole building

tgt_alerted

The person is in the same room as their target man (eg the man he is trying to warn), and the target man is already alert.

tgt_assisted

The person is in the same room as their target man (eg the man he is trying to rescue), and the target man is already assisted.

tgt_moved

The person has moved to their destination (the room occupied by their target man, at the time when the action was commenced), but the target man is no longer there. (By implication, the target man will be alert, and may be assisted as well if he required it)

tgt_to_order

The person's current room contains a man whose action has an urgency level less than 2. However this condition will be false if the person checking already has an action to order someone in their current room to leave, or the tenability of the current room is too high for a 'order_to_leave' action to be allowed.

tgt_to_rescue

The person's current room contains a dependant or unconscious man who is not assisted. However this condition will be false if the person checking already has an action to rescue someone in their current room, or the tenability of the current room is too high for a 'rescue' action to be allowed.

tgt_to_warn

The person’s current room contains a man who is not alert (though may have been alert in the past, and then reassured). However this condition will be false if the person checking already has an action to warn someone in their current room, or the tenability of the current room is too high for a ‘warn_household’ action to be allowed.

6.2.3 Action parameters (allowed DOD, time delay, etc)

One of the assumptions currently made in the CRISP model, which may need to be reviewed, is that the parameters of an action do not depend on the role of the person performing that action. Suggested values for the action parameters are given in the table below.

Table 6-11: Action parameters

ACTION	DELAY (s)	DOD	URGENCY
asleep	9999	4	0
await_rescue	9999	4	2
choose_exit	0	4	2
complete_work	LN(300,200)	3	0
direct_crowd	N(5,2)	3	2
escape	0	4	2
fight_fire	999	4	2
ignore_order	LN(300,200)	3	2
investigate	N(5,2)	2	1
leave_room	0	5	2
make_refuge	N(120,30)	4	2
order_to_leave	0	3	2
phone_call	N(30,15)	3	1
raise_alarm	N(15,5)	3	2
reacting	LN(40,20)	3	1
rejoin_family	0	3	1
rescue	N(15,5)	3	2
rescue_family	N(15,5)	4	2
respond_to_order	N(5,2)	3	2
safe	N(60,20)	5	2
search_own_floor	0	3	2
standard_exit	0	3	2
trapped	5	5	2
unconscious	9999	5	2
waiting	9999	3	0
wake_up	LN(60,60)	4	0

N(x,y) is a Normally-distributed random variable, with a mean of “x” and a standard deviation of “y”. LN(x,y) is a Log-Normally-distributed random variable, with a mean of “x” and a standard deviation of “y”.

The reaction delay time requires some comment. In an experiment performed in the Netherlands (Boer, Winer & Noren, 2004), 18% of car drivers responded before an announcement to leave was made. Of this 18%, half were quite quick, with a reaction delay given by N(42,17) seconds. The other half were slower, with their delay time described by a Gumbel distribution, Gumb(28.8,155). However, looking at the raw data, a reasonable fit was also provided by a Normal distribution, N(170,30). For the 82% who only responded after the PA announcement, their response time was described by a Generalised Extreme Value distribution, GEV(-0.22, 19.91, 33.08). The median value was about 40s, but there was a much longer “tail” to the distribution than for those responding before the announcement, whose distribution was N(42,17)s. The response time for all drivers in the experiment was the time taken for them to leave their cars. There was then a hesitation period before they actually started to head for the exits. The probability distributions for the hesitation period were different, depending on whether the person had responded before or after the PA announcement. The overall delay for reaction and hesitation therefore has an extremely complex distribution, represented by the event trees in Fig 6.4.

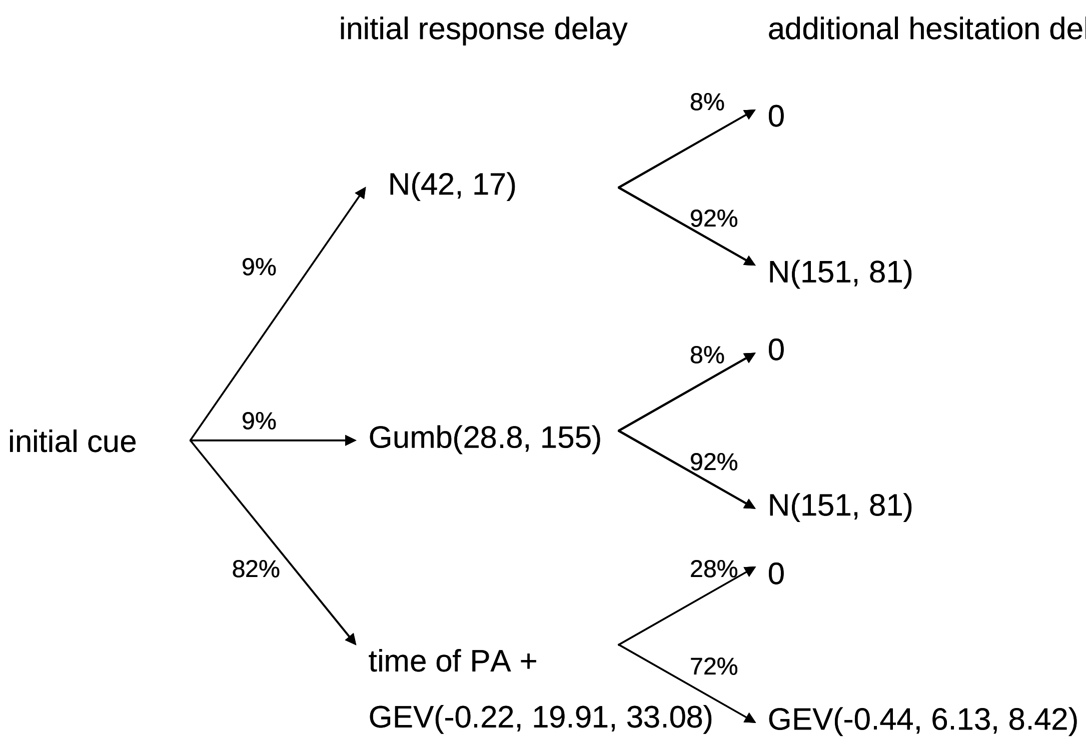


Figure 6.4: The response time of car drivers observed in an experiment in the Netherlands (Boer, Winer & Noren, 2004).

As mentioned above, one of the assumptions made by CRISP is that the parameters of an action are independent of their context, or who is performing the action. In order to replicate the complexity of the response time shown in Figure 6.4 above, no less than six different actions would be required – call these “reacting1”, “reacting2”, … “reacting 6” – each with their own probability distributions. It would also be necessary to increase the number of different types of probability distribution recognised by CRISP, which currently only uses Uniform, Normal and Log-Normal distributions.

6.2.4 Exit choice

Anecdotal evidence abounds for people’s preference for a familiar route, but there has been very little research to quantify this. In an IKEA store, it was shown that shoppers would walk twice as far to use a familiar exit compared to an unfamiliar one (Benthorn & Frantzich, 1998).

If people are familiar with the building, they will exploit short cuts to get to their destination (Still, 2000) (ie. all routes are “familiar”). Thus members of staff leave by fire exits, visitors by the main entrance (Tong & Canter, 1985). In a tunnel, members of the emergency and rescue services (and members of tunnel staff acting in a similar fashion) would be familiar with the tunnel layout, and thus would use the emergency exits. For other people, the tunnel portal corresponds to the "familiar route" and as such will be the most popular exit choice provided it is not too distant.

The various emergency exits, cross-passages to parallel service tunnels and refuges will all look the same until the person actually goes through the door and sees what is on the other side. Thus, whether a door ultimately leads to the outside, or to a dead-end refuge, will not be a factor in exit choice.

The single-bore, two-lane St Gotthard tunnel has a parallel escape route accessed at 250m intervals by ventilated galleries (http://www.construction.com/NewsCenter/Headlines/ENR/20011031b.asp). People on the northern side fled their cars and escaped on foot through the parallel emergency escape route (http://archives.tcm.ie/breakingnews/2001/10/25/story27708.asp; http://www.dawn.com/2001/10.25/int10.htm). Two lorry drivers described how they had to feel their way along the tunnel walls, due to zero visibility conditions, until they found an emergency exit (http://www.guardian.co.uk/international/story/0,3604,581224,00.html; http://www.construction.com/NewsCenter/Headlines/ENR/20011031b.asp; http://www.guardian.co.uk/international/story/0,3604,580344,00.html). In the Mont Blanc tunnel, the side doors led to dead-end refuges instead. Nine of the bodies of the victims were found outside vehicles. Among the drivers or occupants of the cars stuck in line, four left their vehicles. They died of asphyxiation after going about 100 to 500 m (http://www.mrtunnel.com/page3.htm). From the distances travelled, these people would have been able to reach a refuge area, yet did not do so. The bus passengers in the Huguenot tunnel failed to realise that the cross connections were places of refuge, and that they should gather there rather than walk out of the tunnel (Gray & Varkevisser, 1995). The cross-passages were not signed as emergency exits though.

The direction of exit choice will almost certainly be away from the fire. Of the 155 people who died in the Kaprun disaster, 60 had managed to leave the train, but were quickly overcome by acrid smoke as they tried to flee by running upward on narrow stairs leading out of the tunnel (http://www.natives.co.uk/news/1100/12kaprun.htm; http://www.wsws.org/articles/2000/nov2000/aust-n16.shtml; Petrovitsch, 2000). The fire started at the back of the train, so they would have needed to run past the fire in order to go down the tunnel – something which may not have been possible by the time they managed to get off the train. In Baku, the fire also started towards the rear of the train, and the direction of evacuation was to the front of the train. The ventilation system was sending smoke in the same direction (http://home.no.net/lotsberg/artiklar/andersen/en_table_1.html). However due to conditions of almost zero visibility (http://www.azer.com/aiweb/categories/magazine/34_folder/34_articles/34_metro.html, Azerbaijan International (3.4) Winter 1995), people would not have been aware of the direction of smoke movement, so this would not have been a factor in their exit choice. In the Zurich fire, only the passenger who pulled the emergency brake escaped in the direction of Zurich main station. All the other 140 passengers moved away from the fire (Fermaud, Jenne & Muller, 1995).

In an experiment in the Netherlands (Boer, Winer & Noren, 2004), nobody went past the “fire”. This experiment was unusual in that all people used side exits rather than the tunnel portal. The fact that the two nearest exits were only 50m apart (thus the nearest exit was less than 25m away) may well have been a factor here). 94% of people used the nearest exit, and 6% used the first exit they encountered when moving in the driving direction (ie towards the fire).

These behaviours are represented within CRISP by means of the “choose exit” action, which immediately becomes “standard exit” or “escape”, the relative probabilities depending on the degree of familiarity with the tunnel layout. The “standard exit” action will restrict the choices to the exits with the lowest DOD – ie the tunnel portals. The “escape” action will consider any routes not exceeding the allowed DOD for the escape action. The probability of choosing a side exit rather than the tunnel portal can be fixed by adjusting such parameters as the DOD of side exits and portal, the "extra distance" associated with the side exits or the portal, and the weighting factor applied to different DOD's. The "standard exit" action has a lower allowed DOD than the "escape" action, so when conditions deteriorate, people heading for the tunnel portal will revise their exit choice decision, and may decide to head to the side exits instead.

Movement past the fire will be prohibited when the tenability level of the segment of the tunnel containing the fire location worsens beyond the allowed DOD for the "standard exit" or "escape" actions. Similarly, movement towards the fire will be inhibited for different tunnel segments as the smoke conditions worsen.

Directions given by people in "authority" are clearly a strong influence on exit choice, as evidenced by Kings Cross (directions given by British Transport Police; London Underground staff and members of the public were not viewed as "authority" and thus were often ignored) (Canter, Donald & Chalk, 1995), St Gotthard (instructions to back up given by truck drivers, and later police) (http://www.guardian.co.uk/international/story/0,3604,581224,00.html; http://www.dawn.com/2001/10/25/int10.htm), Zurich (directions to the portal given by the train drivers) Fermaud, Jenne & Muller, 1995), San Francisco BART (directions from the train driver; cross-passages to the adjacent tunnel were spaced every 100m) (Chan & McCleery, 1995), etc.

This behaviour is represented in CRISP by the "direct crowd" action. After this is complete, any people within range of the person giving the directions will be ordered to escape by the nearest exit having a tenable route. Generally, this will be one of the side emergency exits.

The effect of tunnel ventilation may be to keep the "upwind" direction fairly free of smoke, while worsening conditions more rapidly "downwind". However, as people are unlikely to move past the fire, this will not be a factor in exit choice.

When all else fails, if people cannot get out then they will attempt to survive as long as possible by making a refuge. In the Tauern tunnel, 4 lorry drivers tried to take cover inside an emergency phone box about 100 meters from their vehicles but only 2 men and a woman managed to do so; the fourth, a 27-year old man, just failed to make it. The other 3 survived for an hour until they were rescued by firemen (http://www.landroverclub.net/Club/HTML/Travel_TauerTunnel.htm). This behaviour is represented in CRISP by the "make refuge" action.

6.3 Interaction within groups of people

6.3.1 Different types of group and group behaviour

The fact that people often (and indeed normally) move in groups, rather than a mass of individuals, is still rarely represented in engineering models of crowd movement. Human cognition, decision-making and behaviour will need as close attention as human movement and hazard growth predictions, if the simulations are to validly represent the time it would take people to escape in reality (Sime, 1993).

As is well known from fires in buildings, social groups tend to remain together. The tightest bonding is exhibited by members of the same family. One of the eyewitnesses to the Tauern fire reported fathers carried children in their arms (The Guardian newspapaer May 31st, 1999). Other witnesses said people were looking for relatives (The Observer newspaper, 30st May, 1999). On the Baku Metro, a mother recounted how her 2 daughters helped her off the train, but as conditions worsened she ordered them to leave her and save themselves (http://www.azer.com/aiweb/categories/magazine/34_folder/34_articles/34_metro.html, Azerbaijan

International (3.4) Winter 1995). People at the Depot finally rescued her. This last example is interesting because it shows the family group breaking up under extreme stress.

Larger groups may be formed by people who have some form of social affiliation. The Mersey tunnel fire started in the engine compartment of a coach, on private hire carrying 40 female passengers who were members of a private party on a social night out celebrating a special occasion (Gillard & Arch, 1995). The size of this group, and the fact that they had consumed a significant quantity of alcohol, required a significant level of resources to take care and control of them.

Ad-hoc groups may be formed by those who have no affiliation beyond finding themselves in the same emergency. A number of incidents have led to groups of people holding on to one-another (due to poor/zero visibility) and moving slowly in single file to the same exit (http://www.azer.com/aiweb/categories/magazine/34_folder/34_articles/34_metro.html, Azerbaijan International (3.4) Winter 1995; Fermaud, Jenne & Muller, 1995; http://onenews.nzoom.com/onenews_detail/0,1227,143887-1-7,00.html; http://onenews.nzoom.com/onenews_detail/0,1227,143633-1-7,00.html). These groups can provide mutual encouragement for their members: "In one of the lighted niches, the man in front of us sat down. I sat down too and told my girlfriend that I wanted to stay there. She became upset, started shaking the man and screamed that he had to go on" (Fermaud, Jenne & Muller, 1995).

Other ad-hoc groups may be formed from rescuers and the dependents they are helping. The rescuers may include members of the public, unrelated to the people they save.

A study of high-rise building evacuation drills (Proulx, 1995) found that carrying babies did not significantly slow people down (0.22 - 0.77 m/s on stairs). Small children (aged 2-5) and elderly moved at a speed of 0.45m/s on stairs. People tended to form groups of 2-3 (family/neighbours) and move at the speed of the slowest.

When a group leader's actions turn out to be unsuccessful, the group may split and / or follow a new leader (Jones & Hewitt, 1985).

Separated individuals respond rapidly but family groups wait until clear sign of fire threat. However, if there are many people witnessing any event they may all tend to assume that it is "someone else's problem".

In cars, it is likely that passengers would take the lead from the actions of the driver. They would therefore do nothing until the driver had responded decisively, whereupon they would respond decisively too.

In the behaviour listed in Table 5-9, a single driver has a 95% chance not to react at once, whereas in a car with (n-1) passengers as well, the chance that none of them react at once is 0.95^n. Once the first has reacted decisively, the "choose exit" behaviour would be interrupted to provide a cue for others to leave – but 82% of the time, another person would ignore this cue.

A better way to represent what should happen (all people in a car going at the same time) may be to have separate behavioural roles for the driver and the passengers. The passenger behaviour would be almost identical to that given in Table 5-9, except that reacting would only be followed by "complete work" and "respond to order" would only be followed by "ignore order". However, "ignore order" would have an extra condition, for the order originating from a member of the same "family", that causes the "rejoin family" … etc sequence to start up.

Another way to achieve the same end would be if car passengers were automatically "re-assured" by their drivers. The concept of re-assurance was first introduced for the simulation of domestic fires (Fraser-

Mitchell, 1994, 1997), where it enabled less senior members of the household to warn others (an action with urgency level 2), and then to be reassured while the more senior members of the household investigated (urgency level 1). A reassured person is only re-alerted when tenability level 2 is reached (a non-reassured person requires tenability level 1), or explicitly warned by others. In tunnels, the car driver would need to “warn household” for the passengers in his car, before proceeding to escape.

Of the two approaches, the former is preferable, because it does not rely on (hardwired) reassurance and re-alerting rules.

The report on the Netherlands experiment (Boer, Noren & Winer, 2004) also suggested the existence of “herding” effects, after the announcement to leave was made on the PA system. Of those people who had not responded prior to this, there was a delay until the first person left their car, whereupon the others followed rapidly behind them. It was also noted in some of the tests, where significant numbers of people left before the PA announcement, they responded shortly after the first of their number had started to leave.

6.3.2 Group Formation and Behaviour within CRISP

In CRISP, each person is modelled as an individual, making their own decisions and moving independently. However, some of the behavioural actions are designed to emulate group behaviour.

Pre-existing groups are handled within CRISP by means of the “family” concept. Originally this arose from a simulation of domestic dwellings, but is now extended to cover all forms of grouping where the people have some knowledge of one-another prior to the fire.

The generation of people within the building uses a probability tree approach. The first level is to define a number of population member types. Each population member type has probabilities for the type of occupation (which in turn determines location probabilities etc as a function of time of day, and various other parameters), and probabilities for the type of behavioural role. This is explained by means of the following example.

```
'occupns.dat'          list of allowed occupations and associated data files
'roles.dat'            list of allowed behaviours and associated data files
3
'adult'        3
               'employed'     0.64    2
                              'leader'  0.25
                              'led'           0.75
               'unemployed'   0.34    2
                              'leader'  0.10
                              'led'           0.90
               'disabled      0.02    1
                              'dependent'     1.00
'elderly'
....
'child'
....
```

Figure 6.5: Format of the CRISP “population members” data file

The file format is as follows:

- The first two lines give files which list allowed occupations, roles, and their associated files (called in this example “occupns.dat” and “roles.dat”, respectively)

- The third line gives the number of types of 'population member' (These members are used in the family profiles in the family data file). In this example, for a domestic population, the broad classification is “adult”, “elderly”, or “child”

- Each member then has several lines of data; the first is the name of the member type (for user's benefit only) and the number of possible occupation types. In the example above, the adult type has 3 possible occupations (“employed”, “unemployed” and “disabled”)

- Each occupation type then has several lines of data; the first contains the occupation name (cross-reference the occupations data file to get the file name giving this occupation's probability data), the probability of having this occupation, and the number of behavioural roles that a family member of this type and occupation may have. In the example above, 64% of adults have the “employed” occupation type, and may have one of two possible behavioural roles.

- Each role has a text string to identify it (cross-reference the roles data file to get the file name giving this roles' behaviour) and a probability that a family member of this type and occupation may have this role. In the example above, employed adults have a 25% chance to behave as “leader”, and 75% chance to behave as “led”. (Note that the probabilities may be different for other branches, for example the unemployed adults only have a 10% chance to be a “leader”)

Frequently, this file may be very simple if there is a one-to-one correspondence between the member type, the occupation and the role (i.e. each member type has just one occupation type, which in turn has just one role).

The ‘family’ is the basic unit of a building population. It may actually represent some form of affiliation between its members, or else simply be a convenient way of expressing the numbers of people present. The ‘family profile’ is a probabilistic description of the numbers of each population member type within the family. Each family has up to 20 possible profiles, with one selected at random according to the respective probabilities. The actual numbers of each member type associated with the chosen profile are then selected randomly, from a uniform distribution between the minimum and maximum numbers specified.

Not only may actual numbers of people be specified, it is also possible to fill up rooms on the basis of population density. A room range is defined, and then a probability distribution specified for either density (people/sq.m) or actual numbers of people. Then the family profiles for an individual family are specified; members of an individual family do have an affiliation to each other, but not to other families. CRISP will then generate as many families as necessary to achieve the required population density or actual numbers in all of the specified rooms.

Note: if affiliation is not required, then an easy way to ensure exactly the desired number of people are created is to specify family profiles with only one person. There should be one possible profile for each population member type; in each profile one of the member types will have max/min values of 1, and all other types have max/min values of 0. The probabilities of each profile then give the proportions of each member type that will be generated.

```
1      (public, cinema screen 1)
8
2                    no of time-based distributions
'1330'  35     -2.0     log-normal distrib of people, 95%  8 - 140 bods (max 350)
```

'2300'	0.0	0.0	all shows over		
4					
0,0	0,0	0,0	1,1	0.05	(one visitor)
0,0	0,0	0,0	2,2	0.80	(two visitors)
0,0	0,0	0,0	3,4	0.10	(three or four visitors)
0,0	0,0	0,0	5,8	0.05	(five to eight visitors)

Figure 6.6: Part of a CRISP "families" data file.

In the example in Figure 6.6 above, the families will all be confined to a single room (i.d. number 8), and the total number required depends on the time of day. Between 1300-2300 the total number will follow a LN distribution, with 95% confidence limits from 8 to 140 people. Outside these hours the room #8 will be empty. Families will be created until the required total number of people are present. The distribution of family sizes is: 5% - 1 visitor, 80% - 2 visitors, 10% - U(3,4) visitors, and 5% - U(5,8) visitors. There are none of each of the other three population member types.

1	(public, road tunnel)				
...					
...					
4					
0,0	...0,0	1,1	0,0	0.50	(one driver, no passengers)
0,0	...0,0	1,1	1,1	0.35	(one driver, one passenger)
0,0	...0,0	1,1	2,2	0.10	(one driver, two passengers)
0,0	...0,0	1,1	3,4	0.05	(one driver, 3-4 passengers)

Figure 6.7: Part of a possible CRISP "families" data file for a road tunnel: people in cars. (Probabilities are arbitrary, for illustrative purposes only). Here two population member types may exist in one family – drivers and passengers. Other population members (eg tunnel staff, emergency / rescue services) will (obviously) not be present in these "families".

Each person within CRISP knows who the other family members are. This information is used by two behavioural actions, "rejoin family" (section 4.3.1.18) and "rescue family" (section 4.3.1.20).

People in CRISP may also rescue other people who are not part of their family (section 4.3.1.19). The requirement for a person to be rescued is that they are either of a "dependent" behavioural type, or are unconscious. The person doing the rescuing is restricted by his behavioural rules regarding the circumstances in which rescue behaviour is allowed.

When a person has been successfully rescued, various pointers are set so that the rescuer, and the person being rescued, remember who they are linked to. The person being rescued is also flagged as "assisted", so that when it is their turn to make decisions, move, etc, all they do is to join up with their helper (who continues to move independently). The encumbrance is representing to setting the head height of the rescuer to 90% of normal, and reducing his movement speed to 30% of normal (may be excessively severe, especially if the person being rescued is a baby, or is ambulant – review). The helper will attempt to escape, and the person being rescued will join him at each time step. If the helper makes it to safety, the person being rescued will become safe too.

People in CRISP may form ad-hoc groups in certain circumstances. When they do so, certain decisions are delegated to the group leader. Others continue to move independently, but don't change their behavioural action.

The requirements for a person joining an ad-hoc group in CRISP are quite stringent. The person potentially being followed must have:

- the same current room
- the same behavioural action
- the same next door on their route, and be nearer to it than the person attempting to join the group
- the same ultimate destination, but not have reached it yet

There is also a clause that one or more of the following must be satisfied:

- the person trying to join the group may not be carrying someone (as part of a rescue – escape behaviour sequence), or
- the person potentially being followed must be independent or a group leader, or
- the same behavioural action

(The rationale behind some of these criteria has become somewhat obscure).

If there is more than one person who could potentially be followed (!), the successful candidate will be the one who is nearest to the person wanting to join the group.

The group leader will leave the group (and maybe then attempt to join another group) when he changes his position from one room to another. Group leadership will then pass to the person who was following the previous leader. The reason for the group leader abandoning the group was to avoid any changes in behaviour triggered by conditions in the new room having an effect on the rest of the group, before the rest of the group would have had a chance to react.

The purpose of this algorithm was two-fold:

1. To reduce the number of people making decisions on each time step, and therefore speed up the model execution
2. To get a group of people to move "together" at the speed of the slowest.

A person in a group adjusts their movement rate to be the minimum of their own speed, the speed of the person they are following, and the speed of the person following them. On future time steps, the effect of slow movers further up or down the chain will have an influence (since the movement rates aren't reset to the default individual rates while people are moving in groups).

6.4 Effects of luggage on behaviour

6.4.1 Behavioural actions associated with luggage

Only a few anecdotes regarding tunnel fires refer directly to passengers with luggage and other belongings. On August 1, 1970, a fire in the tunnel of the New York City subway near Bowling Green killed 1 and injured 50. The one death occurred when a woman, who returned to the train to retrieve her purse, died of smoke inhalation (http://www.nycsubway.org/faq/accidents.html). It was suggested that some of those people killed in the St Gotthard had reached safety but returned to their vehicles to retrieve items left behind (http://www.cnn.com/2001/WORLD/europe/12/21/tunnel.reopen/?related). Whether other people remembered to take belongings with them, or instead left them behind, is not known.

The Huguenot tunnel fire started on a moving bus, which then crashed into the tunnel wall. Despite this, the CCTV recording showed passengers leaving the bus in an orderly manner and attempting to retrieve their belongings from the roof rack (Gray & Varkevisser, 1995). In contrast, passengers lost all their luggage in a coach fire in the Homer Tunnel, NZ (http://onenews.nzoom.com/onenews_detail/0,1227,143887-1-7,00.html).

A railway official reported personal knowledge of a detrainment, where the passenger population included passengers attempting to evacuate with their luggage (Galea & Gwynne, 2001). Procedures for the evacuation of Heathrow Express Trains recognise that people do not want to abandon their luggage; if people wish to take their luggage, they are instructed to wait behind until all other passengers have left first (French & Stevens, 1999).

6.4.2 Effect of luggage on movement speed

Observations have been made of people alighting from trains, with and without luggage (Boer, Winer & Noren, 2004). It was concluded from these observations that the width of the door (from 0.75m to 1.4m depending on the type of train) did not significantly affect the flow rate. The flow rate was expressed in terms of people per metre width, rather than per metre of effective width, so this conclusion may not necessarily be correct.

The effect of luggage was to slow the flow rate by about 50%, from about 1.4pers/s to 0.7pers/s. For other types of train, where there was a difference in height between the train and the platform of about 0.3m, the reduction in the flow rate was less marked, about 70%. However the flow without luggage was much slower with the 0.3m drop than without, so the flow with {luggage + drop} was slower than with luggage only and no drop.

The effect of luggage may simply be to increase the density of the flow without increasing the density of people. If the floor area occupied by the people is A_p, and that occupied by the luggage is A_l, then the flow rate of people is reduced by a factor $A_p/(A_p+A_l)$ compared to the flow rate of people with no luggage (all the area A_p+A_l occupied by people).

6.5 Other considerations

6.5.1 Movement in darkness

Jin and Yamada define light extinction coefficient C (units 1/m) by

$$C = -\ln(I/Io) / L$$

where I is the transmitted light intensity, Io the initial light intensity, and L is the light path length (m). The light extinction coefficient is related to optical density D by C = 2.3 D.

For smoke where $C<0.3\text{m}^{-1}$ there is little effect, normal speed is 1.2m/s. Non-irritant smoke reduces speed to 0.3m/s when $C \sim 1.2\ \text{m}^{-1}$; irritant smoke reduces speed to 0.3m/s when $C = 0.5\ \text{m}^{-1}$. (Blindfolded people move at 0.3m/s) (Jin & Yamada, 1985).

The limit to what most people will endure (Jenssen, 1993a) is irritant smoke at OD 1.53 - 2.26/m, exposure 3-4 minutes, escape path 25-30m, speeds 0.2-0.5m/s. Those who survive moving in smoke travel an average distance of 9.1m; only 10% go further than 16m.

6.5.2 Traversing changes in height

In order for passengers to leave the train normally by the side doors (the fastest mode of evacuation), the train must be in a station. If only part of the train is in the station (http://news.bbc.co.uk/1/hi/england/2694503.stm), some passengers may have to move between carriages via the end doors, which are usually quite narrow and therefore introduce a significant delay.

In more severe yet still favourable circumstances, it may be necessary to evacuate passengers to the track level. Passengers may use side doors (if the tunnel is wide enough) or the end door. Ladders may be available to assist the descent (typical drop is about 1m). In one incident (Galea & Gwynne, 2001), 400 passengers required about 1 hour 20 minutes for the passengers to descend to track level. This equates to an average of 12 seconds per passenger to negotiate the exit and ladder. The passenger population in this incident included elderly and infirm people and passengers attempting to evacuate with their luggage.

In another incident (Rose & Harding, 1993), every passenger had to pass through the train end door, 495 mm wide, then descend a wooden ladder with four steps (a vertical drop of 1.2m).The actual full-scale detrainment started at 0858, and was completed at 1330. In the event both directions were used, and even if numbers were evenly distributed, this represents one person for six seconds in each direction. (It is not clear whether the passengers took their luggage with them on this occasion.)

In some situations it may not be possible to use the carriage doors during an evacuation, and passengers will try to break windows instead.

The most difficult evacuation of all would involve an overturned, smoke-logged rail carriage. Two full-scale evacuation experiments were performed (Galea & Gwynne, 2001), in one of which the participants were subjected to non-toxic smoke. Only a single run of each trial was undertaken with a limited – and uninjured – population. In the evacuation involving smoke, the carriage and exit was found to achieve an average flow rate capacity of approximately five people a minute. Without smoke the flow rate was found they approximately 9.2 people a minute. Due to the nature of experimental conditions, these flow rates are considered optimistic. Fortunately, such a situation has not yet occurred in a tunnel.

In CRISP, the flow rate through doors is determined by the effective width of the door. People are required to wait on the door threshold until the model allows them to proceed; the delay time is such that the theoretical flow rate for the given door width is not exceeded (Fraser-Mitchel, 1999). Where there are significant differences in height, the delay time at the threshold should be modified accordingly.

There is also a time delay in CRISP for the action of opening a closed door or window. In the case of rail tunnels, where passengers have to force doors open, or smash windows, this can be accomplished by setting the opening time to a suitable value.

Height differences are not only restricted to rail tunnels. In the Hatfield and Heathrow tunnels, walkways are on raised ledges, which only able-bodied people could use (Marchant, 1999).

6.5.3 Disabled (or less able) people

Although there are many different forms of disability, the major effects on egress performance are likely to cover movement speed, ability to negotiate obstacles, and stamina. Parameters of the probability distributions for movement speeds of different locomotion aids have been determined. Disabled people do not necessarily move more slowly than able-bodied people on a flat surface (Boyce, Shields & Silcock, 1999a, 1999b; Shields & Boyce, 1995; Pearson & Joost, 1983), but inclines are more challenging, and stairs may be impossible without assistance. Ramp slopes should be less than 1 in 15 for wheelchair access (Lischer, 1993). The terrain in a tunnel may be unsuitable for some types of movement aid. This will be more of a problem in rail tunnels. For example, passengers in wheelchairs may have to abandon them and be carried instead (Chan & McCleery, 1995). Following the Bethnal Green incident, London Underground now provides "carrying sheets" for evacuating any disabled customer in the event of detrainment (Rose & Harding, 1993).

In the USA, the production of the Americans with Disabilities Act included studies of disabled egress times. This work concluded that average disabled egress velocities were 27 m/min, with a requirement to rest for 2 minutes every 30 metres. “This gives an average velocity of 9.7 m/min per 3.11 minute interval.” (0.15 m/s). This figure needs to be considered in relationship to the average walking velocity of unimpeded persons of at least 72 m/min. (1.2 m/s). However the movement speed in darkness is 0.3m/s, so here the difference between disabled people and others is less pronounced.

Even if messages are given, they may not always be received or understood. In public assembly buildings, the following percentages of the total population were disabled (Boyce, Shields & Silcock, 1999; Shields & Boyce, 1995): sight - 1.4% (0.01% blind), hearing - 2.2% (0.24% deaf), mental 2.2%, etc.

Some people who would not normally be considered “disabled” may effectively be so. In the Mersey Kingsway tunnel, the passengers of the bus had consumed a significant quantity of alcohol ((Gillard & Arch, 1995), which appeared to impair their behaviour. Pregnant women may also require special treatment (http://www.railways.dft.gov.uk/ctsa/18nov96/chap8.htm).

Bodies of victims can be an obstacle to others, as illustrated by eyewitness accounts of the Baku Metro fire (http://www.azer.com/aiweb/categories/magazine/34_folder/34_articles/34_metro.html, Azerbaijan International (3.4) Winter 1995). In CRISP, unconscious people still occupy space, thus causing an obstruction. If it is not possible to move around them, then they can currently be “shoved” (into a vacant pixel) but not “jostled” (swap pixel with the man trying to occupy their space). These rules may need to be reviewed for unconscious people.

6.6 Preliminary results

CRISP has been used to simulate a tunnel fire, but this was only a demonstration of the model's capability rather than a serious study (Fraser-Mitchell, 2003). It did however include a growing fire, spreading smoke, and people interacting with the smoke.

The behaviour of the people was deliberately very simplified for demonstration purposes. In particular, as soon as a person was alerted, they immediately escaped (with no time delay for reaction). However, people were not all alerted at the same time, but only when the smoke had reached them.

Table 6-12. Behaviour of people, simplified demonstration example

ACTION		CONDITION		NEW ACTION(S)
escape	o	complete	------- ----->	safe
	o	no_route	------- ----->	trapped
leave_room	o	complete	------- ----->	previous
	o	cannot_leave	------- ----->	trapped
reacting	o	complete	------- ----->	escape
	o	no_route	------- ----->	escape
safe	o	complete	------- ----->	safe
trapped	o	complete	------- ----->	previous
unconscious	o	complete	------- ----->	unconscious
waiting	o	complete	------- ----->	waiting
	o	alerted	------- ----->	reacting

Table 6-13: Parameters associated with actions, simplified demonstration example

ACTION	DELAY (s)	DOD	URGENCY
escape	0	4	2
leave_room	0	5	2
reacting	0	3	1
safe	9999	5	2
trapped	N(5,5)	5	2
unconscious	9999	5	2
waiting	9999	4	0

The following pictures show screen shots of a CRISP demonstration simulation of a tunnel fire scenario.

The yellow strip is a plan view of the tunnel. The portion simulated has a length of 690m, a width of 9m and a height of 6m. The tunnel has been artificially sub-divided into a number of segments, 30m long. In three of the segments (the middle one, and the two that are one segment in from either end), there are emergency exits which people may use. The small black dots are the individual people. The segments get darker as the tenability worsens. A red spot represents the fire, which gets larger as time goes on.

The blue strip represents the cross-section temperature distribution within the tunnel segments. At the start of the simulation, there are only cold air zones, no hot smoke layers. The numbers above and below the blue strip are the temperature rises (K). The segment containing the fire location has an extra number above it, this is the average plume temperature. The small spikes are the people (sitting down while “waiting”, standing up once “reacting”), and the tallest spikes are the doors to the emergency exits.

The lowest strip (initially white) represents the cross-section optical density distribution within the tunnel segments. Also, the red lines represent the pressure differentials as a function of height at the segment boundaries. A positive differential is defined as P(left) – P(right) > 0, and shifts the line to the right of its initial position (P=0).

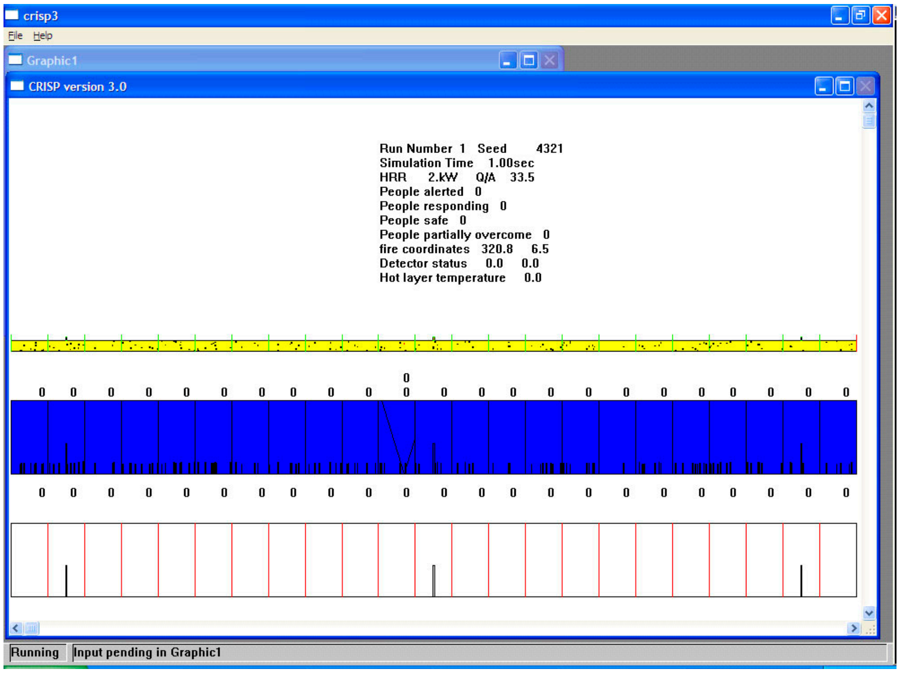


Figure 6.8: Screen shot of CRISP demonstration simulation of tunnel fire scenario. Initial situation.

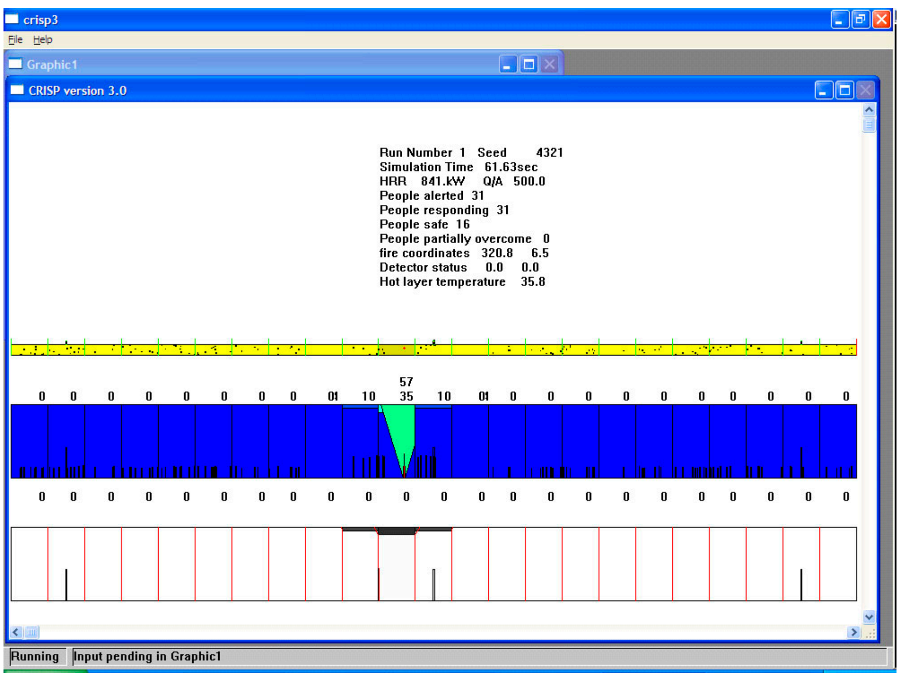


Figure 6.9: CRISP demonstration simulation of tunnel fire scenario. t=1 minute.

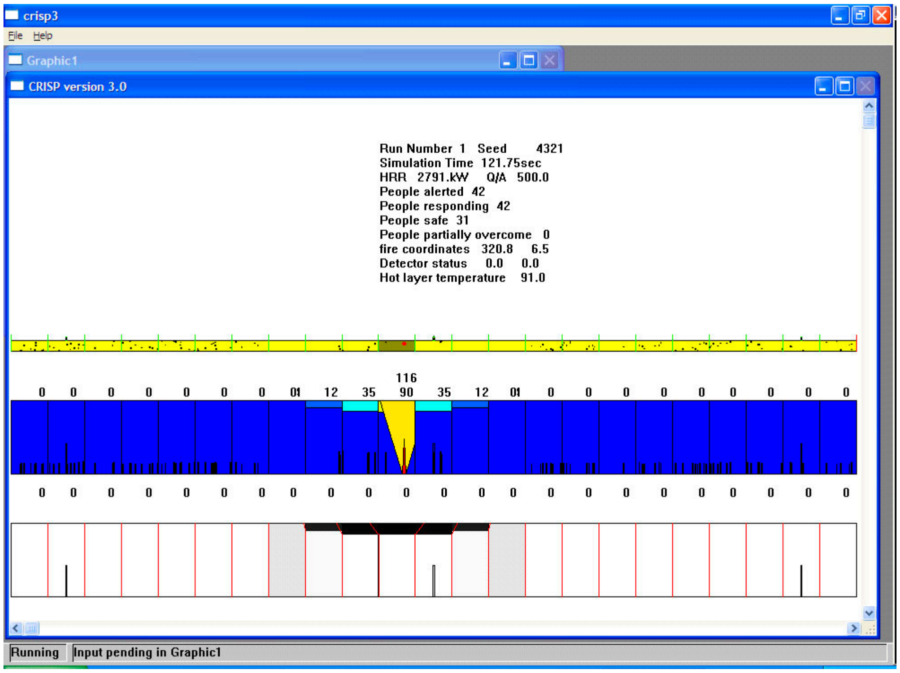


Figure 6.10: CRISP demonstration simulation of tunnel fire scenario. t=2 minutes.

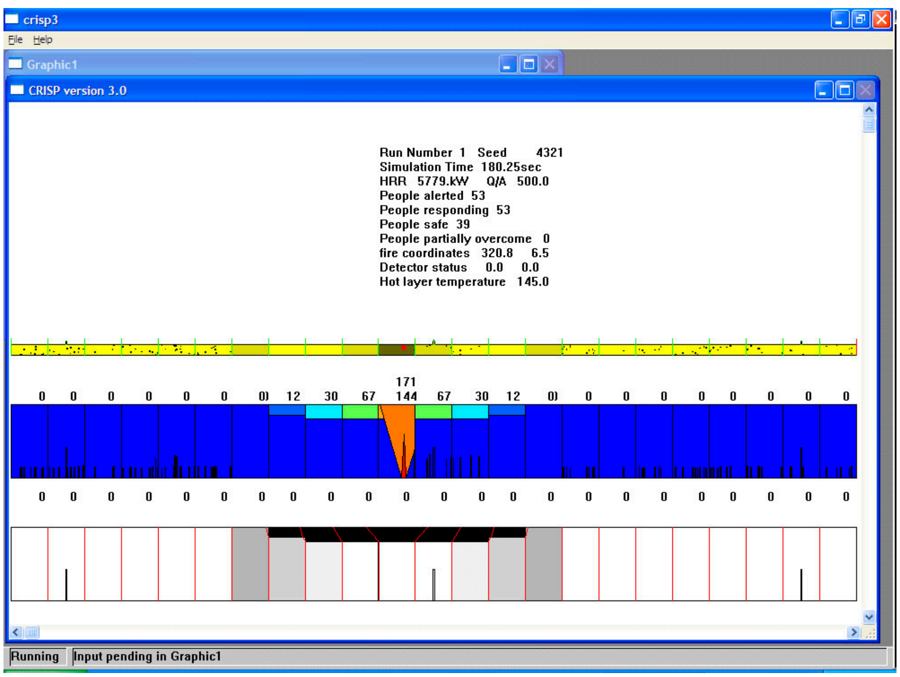


Figure 6.11: CRISP demonstration simulation of tunnel fire scenario. t=3 minutes.

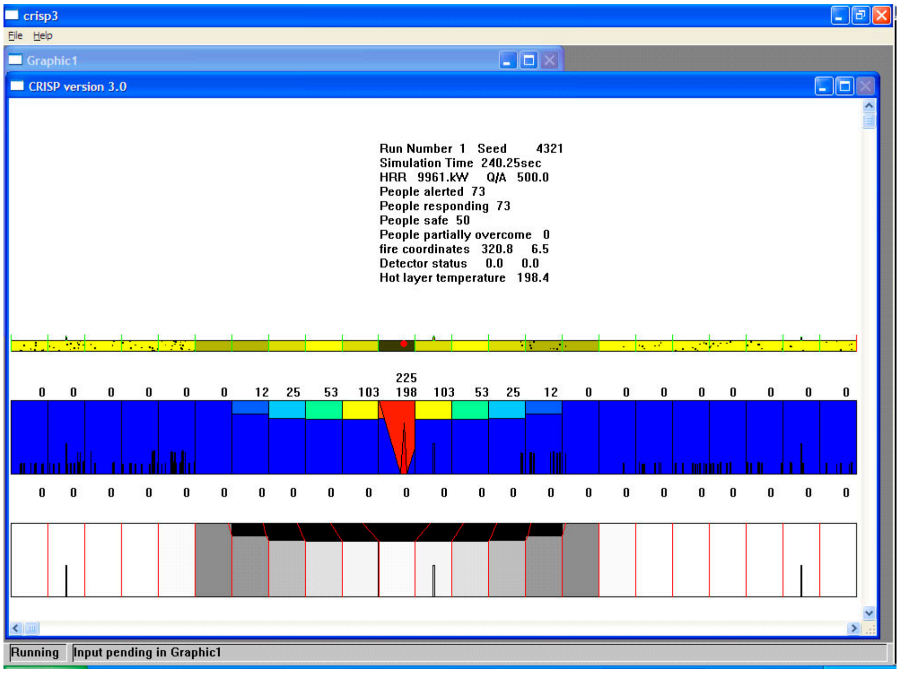


Figure 6.12: CRISP demonstration simulation of tunnel fire scenario. t=4 minutes.

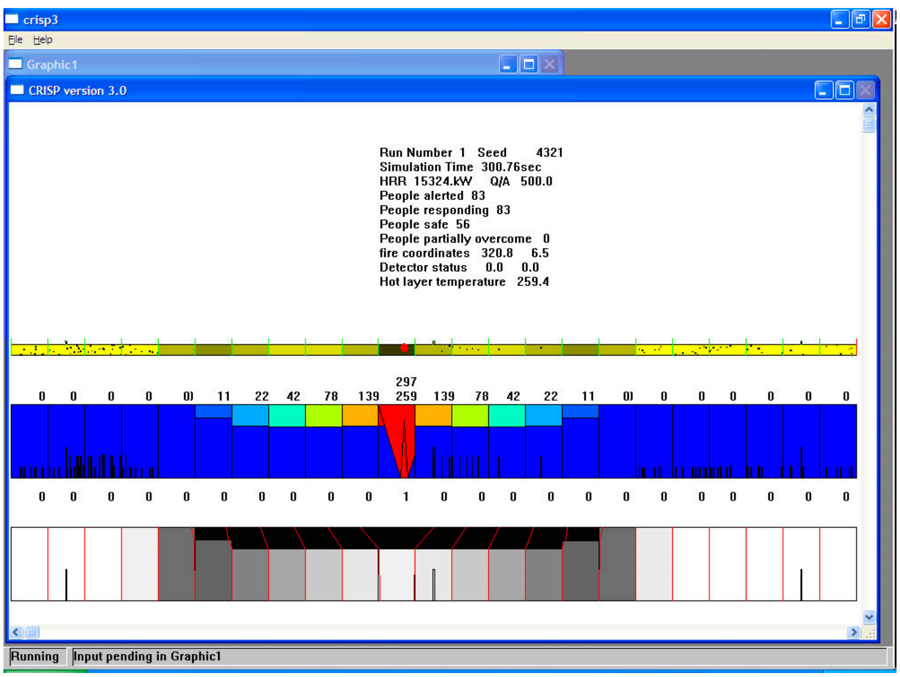


Figure 6.13: CRISP demonstration simulation of tunnel fire scenario. t=5 minutes.

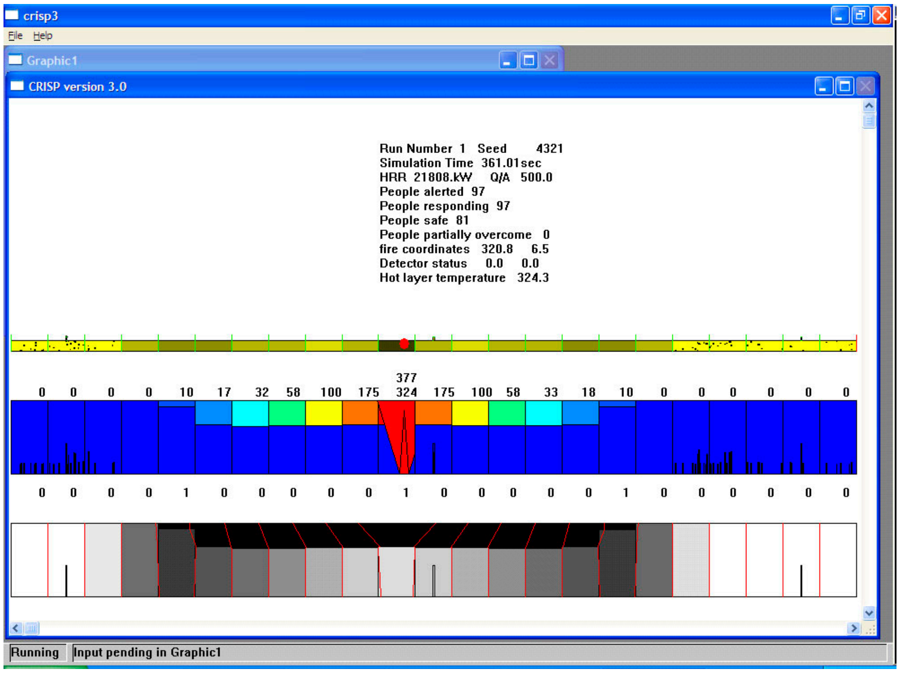


Figure 6.14: CRISP demonstration simulation of tunnel fire scenario. t=6 minutes.

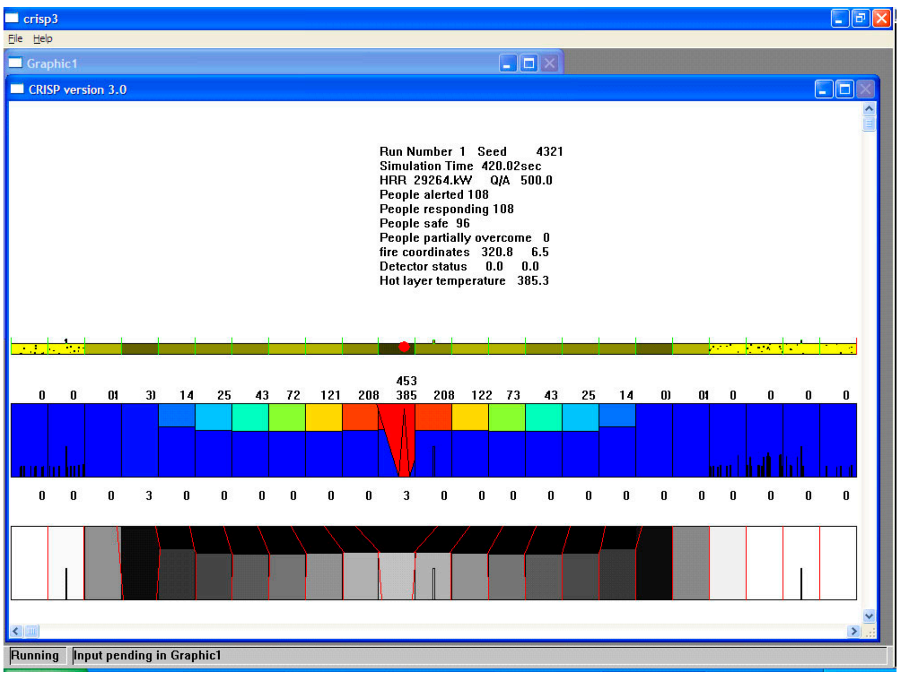


Figure 6.15: CRISP demonstration simulation of tunnel fire scenario. t=7 minutes.

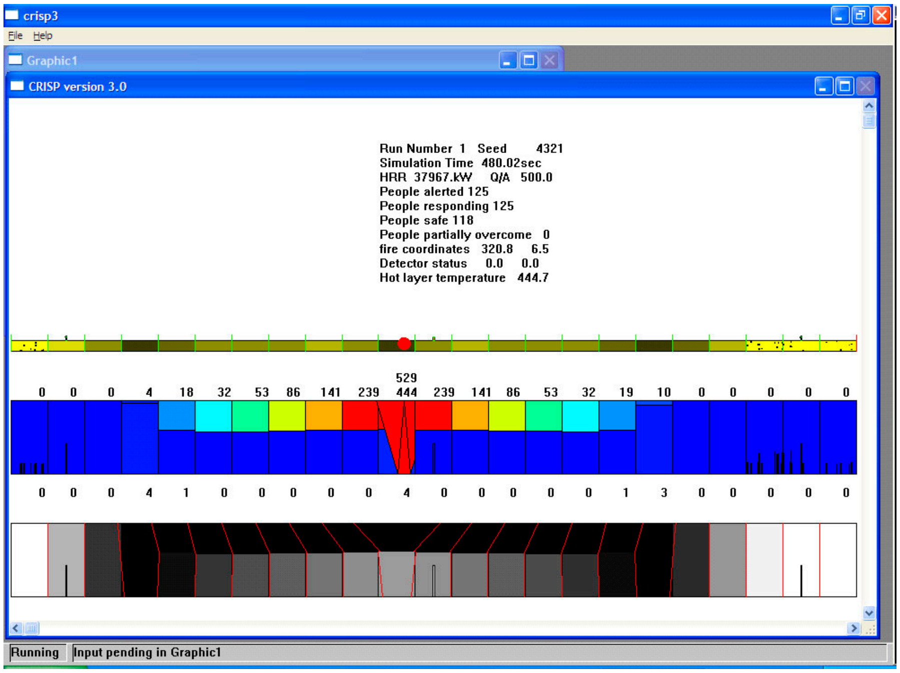


Figure 6.16: CRISP demonstration simulation of tunnel fire scenario. t=8 minutes.

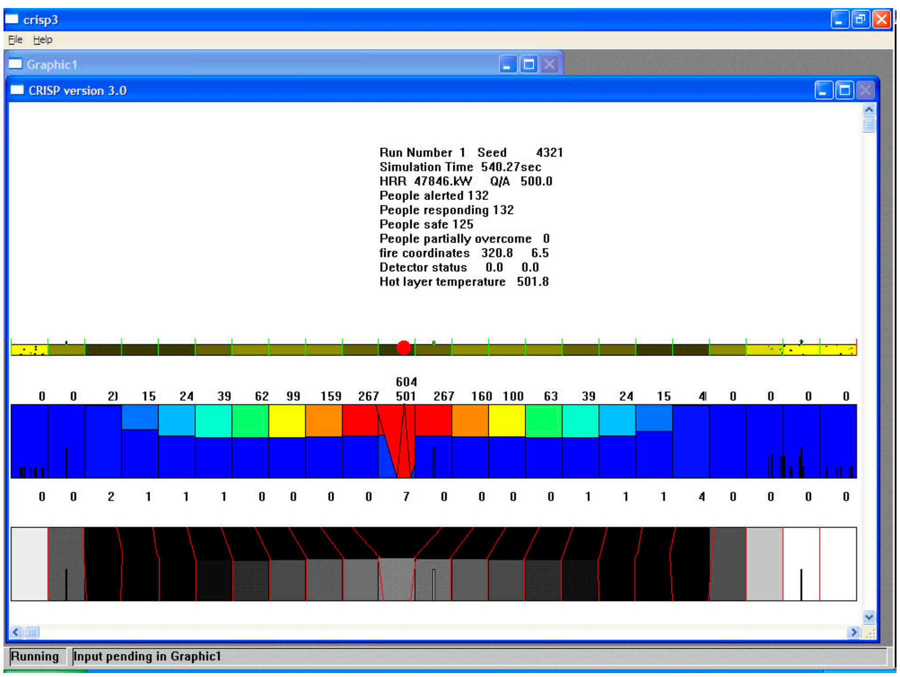


Figure 6.17: CRISP demonstration simulation of tunnel fire scenario. t=9 minutes.

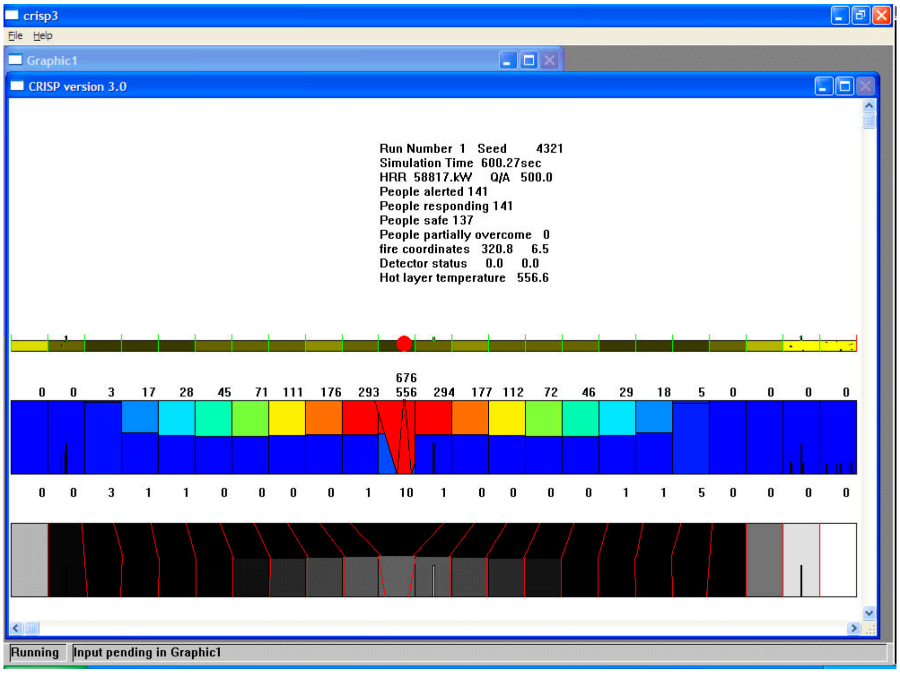


Figure 6.18: CRISP demonstration simulation of tunnel fire scenario. t=10 minutes.

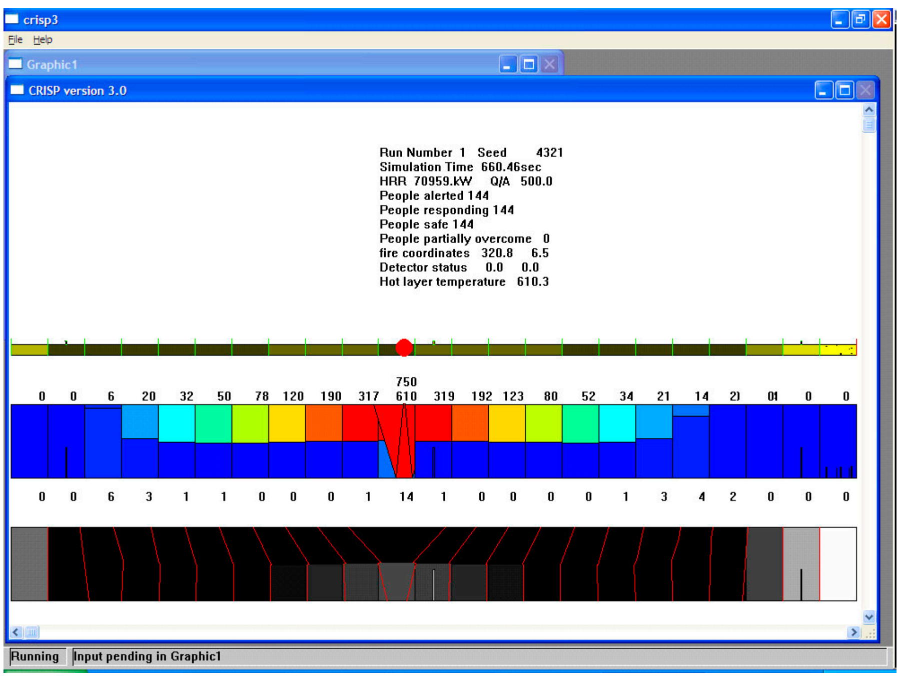


Figure 6.19: CRISP demonstration simulation of tunnel fire scenario. t=11 minutes.

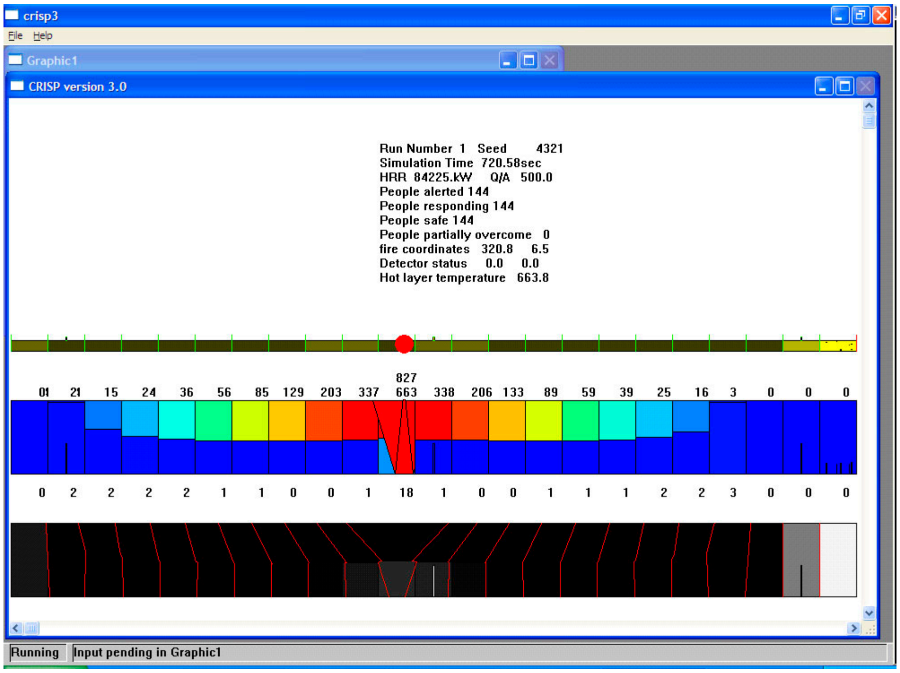


Figure 6.20: CRISP demonstration simulation of tunnel fire scenario. t=12 minutes.

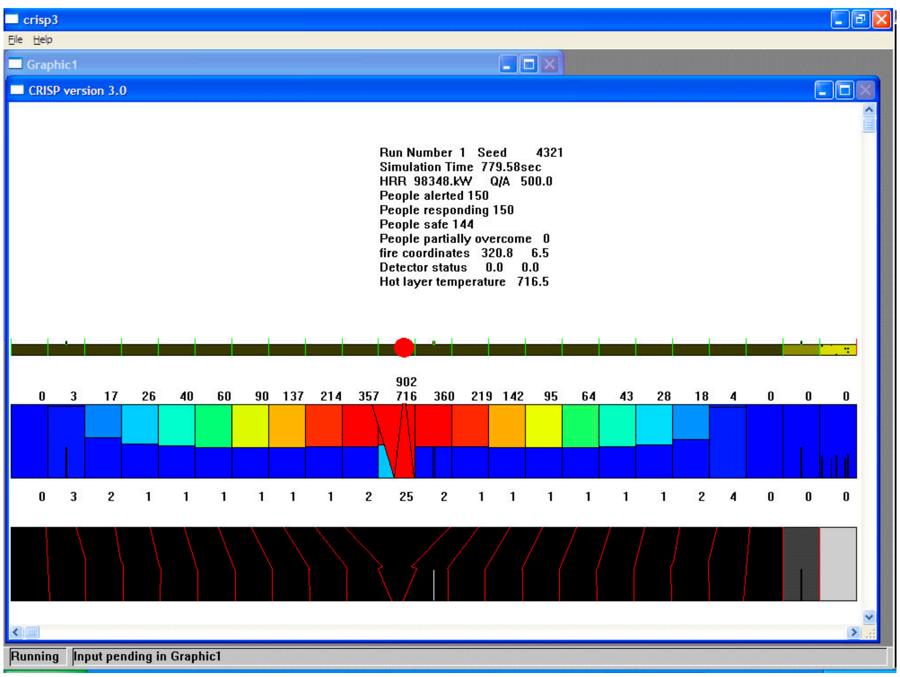


Figure 6.21: CRISP demonstration simulation of tunnel fire scenario. t=13 minutes.

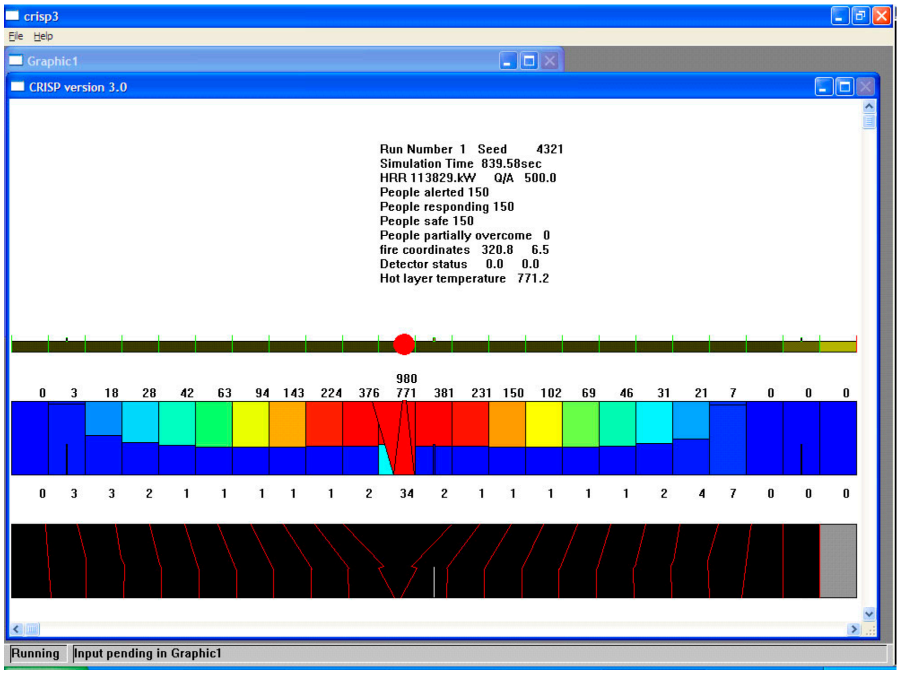


Figure 6.22: CRISP demonstration simulation of tunnel fire scenario. t=14 minutes.

6.7 Conclusions and future work

Previously, CRISP was identified as one of the most appropriate models for human behaviour in tunnel fires. The salient features of CRISP were reviewed, in particular the decision-making process and the way it is influenced by smoke and people's assessment of the tenability level. The behavioural rules that govern what people do are defined in terms of actions (where to go, and how long to pause at the destination to complete the action), and conditions which cause the current action to be abandoned in favour of something else. Each behavioural role has its own rule set.

Examining the reports of actual tunnel fires in detail revealed slight differences in behaviour depending on whether the tunnel was road or rail. This led to the development of the following behavioural rule sets:

- Train driver / train staff / rail tunnel staff
- Coach or bus driver / road tunnel staff
- Rescue / emergency services
- Rail tunnel public
- Road tunnel car drivers
- Road tunnel passengers
- Dependent members of the public (eg. disabled, young children, etc)

Most of the actions and conditions required in the above rule sets have already been developed in the context of building fires, and simply required different parameter values such as the allowed tenability level before abandonment, delay time distributions at completion, etc. These values are rather subjective, although there is some detailed data on the reaction times for car drivers, based on experimental trials.

Exit choice probability distributions have been simplified to a probability of heading to the nearest portal, or the nearest side exit (in both cases provided that a tenable route exists).

Various options for people moving in groups were described. Groups may include families, people with some prior social affiliation, rescuer / dependent pairs, and other ad-hoc formations.

The effect that luggage may have on people's behaviour and movement has been considered. One way in which this may be simulated is to regard large items as a class of dependent "people", needing to rescued, slowing the movement speed of the rescuer once the luggage is being carried, and obstructing the movement of other people.

In rail tunnels, there may be a significant drop in height from the train to the track, walkway or platform. Currently in CRISP the flow rate of people through doors is limited by the effective width of the door, but it would be a simple matter to include the height difference as another factor in the time delay.

Preliminary results from a demonstration application of the model were presented.

7. INNOVATIVE EVACUATION SYSTEM

J. Ellis, D. Gibson & D. Brenkley

MRSL, UK

7.1 Introduction

A simple-to-install novel fire detection/evacuation support system has been developed with some unique features. The main feature is the use of a single wire loop to provide power in a contact-less fashion to each beacon (outstation) via inductive power transfer. This avoids the overhead of local power supplies and the cabling and multi-pole connector problems associated with conventional approaches. The system design offers fail-safe behaviour, with each beacon activated when the charging line is broken or de-energised. The benefits of contact-less operation include; electrical isolation of individual units, guaranteed charge current sharing, the possibility of meeting high environmental protection standards (including submersed operation) and a key benefit – simplicity of installation and the opportunity for temporary deployment. Additionally, the same wire loop is used for data telemetry: the beacons can be interrogated and sensor data can be received from each unit by a central master controller. This offers a capability to monitor environmental conditions at each beacon location and to reassign the evacuation route.

The following sections of this report review specific issues to do with way-finding and evacuation support, and summarise the range of guidance techniques available for evacuation support applications. Experience from evaluating these techniques is also reported here.

A description of the fire detection and evacuation support system is presented in Appendix 9. The description is in the form of a 'product data sheet' and includes an appropriate level of engineering design data and technical commentary, which will be essential in considering further development and commercial exploitation of the research.

7.2 Review of Tunnel Guidance and Way-finding Research

This section summarises information on previous research drawn from the mining and tunnelling sector, which includes passive and active way-finding assistance techniques. These initiatives have been introduced into these industry sectors to improve emergency response and control oxygen cost associated with escape and rescue. There is a body of US research aimed specifically at assisting rescuers in smoke-filled tunnels, primarily undertaken by NIOSH Pittsburgh Research Centre [Conti et al 1999, Conti and Chasko 2001]. It is noted that in the coal mining industry, both fires and explosions pose major hazards. It is worth reflecting on practices from these industries in that a number of different approaches have been evaluated, and there is scope for useful technology transfer to road, rail and metro tunnel applications. One key issue to note is that support systems intended for the workplace can reasonably assume that individuals have received training and instruction in the use of the system, or interpretation of alarms etc. It is not realistic to assume this in a tunnel environment and this requires that system designers give particular emphasis to human factors, ergonomics and behavioural response to systems.

7.2.1 Passive Guidance Systems

Where experienced underground workers have a good understanding of the layout of the area in which they work, together with the location of equipment and plant, they can use appropriate structures such as conveyors, cables and rails as a lifeline in conditions of nil visibility. This 'cognitive map' mental model of the infrastructure may be helpful during fires but is of less value after an explosion. Experience of explosions indicates that damage may be extensive with distorted and damaged structures possibly making the tunnel impassable in low visibility conditions. An alternative approach is to use purposely installed lifelines that lead along escape-ways directly to refuge bays. Having located the lifeline, it is imperative that individuals continue along the line in the appropriate direction towards safety. In an attempt to provide unambiguous direction of travel, lifelines have been adapted to provide unidirectional travel or tactile directional cues. An example of a low cost lifeline from the US mining industry is given in Figure 7.1 below:

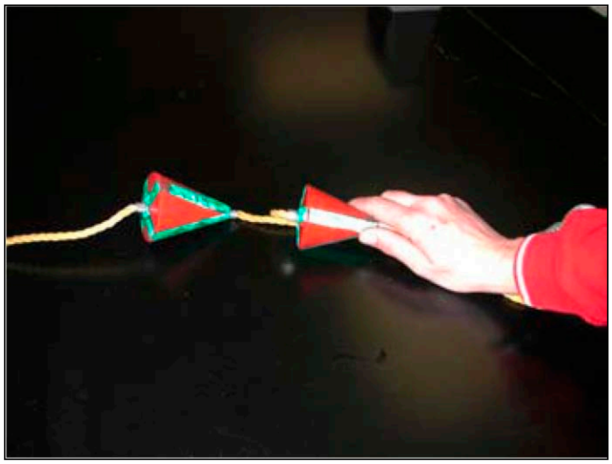


Figure 7.1: Example of low cost lifeline with in-built tactile directional cues

There are at least five different types of lifeline in use (UK HSE, 1997). The utility of installed lifelines has been tested under simulated conditions (Rensburgh et al 1995). The results showed that on average, subjects wearing SCSRs and operating in nil visibility, move at approximately 75 per cent of normal walking speed when aided by a lifeline; the corresponding figure was less than 40 per cent when using only the existing structures in the work area. However it is necessary to train the workforce to grip a simple wire lifeline, with either left or right hand, kept consistent for the entire mine, to preserve correct direction of travel. Alternatively as noted previously, the lifeline can be equipped with directional indicating cones. There is some argument as to whether this results in ambiguity in deciding whether the cones represent an arrow, or whether they are designed to butt up against a hand moving in the wrong direction. Again, effective training and emergency incident rehearsal can resolve these matters. Obviously, the option of training and emergency incident rehearsal is not feasible for tunnels. However, there is a degree of instinct employed in terms of following built structures in nil visibility. Figure 7.2 shows a thermal image of a subject using the tunnel wall as a passive guidance mechanism (Boer, 2002b).

Figure 7.2 : Thermal image of subject using wall for guidance in low visibility (after Boer 2002b).

7.2.2 Active Guidance Systems

In an effort to provide a more effective and general-purpose means of guidance, active electronic guidance systems have been developed, which employ visible and audible signals to guide personnel. A number of systems have been installed in mines in Australia and the Republic of South Africa (Dhar, 1997).

Evaluation of one system was carried out under simulated escape conditions with very low visibility conditions in South Africa, where it was found that escape time was still of the order of three times that measured under normal vision circumstances (Phillips et al, 1997). One further imperative requirement of any guidance system is that it should clearly show where refuge entrances or fire safety doors are located. There have been a number of recorded incidents where workers have been unable to locate a refuge entry, in spite of being in its direct proximity. Several audible, physical and tactile methods have been examined to attract attention, typically involving rotating lights, sirens and roof-mounted curtains. Whatever system is used, it should be consistent throughout the site and made familiar to the workforce on a regular basis.

In addition to the results reported by Phillips et al, evacuation tests have been reported by Rensburgh et al (1995). A number of mechanical and electronic guidance systems were evaluated. One system, the MOSES system, is designed to guide personnel from the workplace to a temporary refuge or place of safety. This is accomplished by a series of small, roof-mounted beacon units spaced at intervals varying between 30-50 m, which emit both an audible and visual signal in a cyclical routine. The cycle commences at the working area and terminates at the refuge chamber. Results of trials to determine the effectiveness of the MOSES guidance system in aiding workers to escape to a safe place, suggested that the speed of locomotion was significantly reduced where only the audible signal was used. From the data contained in Table 7-1, the speed of locomotion during a simulated escape using both audible and visual directional cues was on average 1.83 ms^{-1} and the average evacuation duration was 8.5 minutes. When the evacuees were blindfolded, and therefore had to rely entirely on the audible signal to direct them, the average speed of locomotion was reduced to 0.67 ms^{-1} and it took the evacuees 25.3 minutes on average to reach the termination point.

Table 7-1 : Underground evacuation trial results for MOSES audio-visual beacon system

	Visual and Audible Signal		**Audible Signal Only**	
	Duration (minutes)	Speed of Locomotion (ms^{-1})	Duration (minutes)	Speed of Locomotion (ms^{-1})

Mean	8.5	1.83	25.3	0.67
Standard Deviation			0.82	0.21
Range			14.5 – 39.5	0.39 – 1.07

As a general observation, the use of these systems would not be appropriate for vehicular and rail tunnels. In the industrial environment, training in the use of these systems would be expected. For application in tunnels, the generality of the vehicle tunnel entrants would not be expected to possess any specific emergency preparedness skills or training. Any evacuation support system must be highly intuitive in its operation. The use of directional arrows, carefully worded information signs or pictograms, and possibly spoken annunciations are likely to be required. The use of widely spaced visual beacons is also considered to be of very limited value in trying to way-find through dense smoke. The difficulties in localising sound in smoke are noted, and which are discussed later.

7.2.3 Evacuation Systems in the Non-Tunnel Environment

Increasingly, emergency way-finding lighting systems are being specified to provide guidance on escape routes in occupied structures including buildings, passenger ships (IMO, 1993) and offshore structures (Webber and Ship, 1996). These systems, which are normally electrically powered, come into action automatically when normal lighting fails or when smoke is detected. There and Weyman (UK HSE, 1997) have examined the value of non-mining evacuation systems, principally to derive design guidelines and good practice. They report that effective visual systems can permit speeds of travel of between 0.2 and 0.5 metres per second in smoke logged buildings. However, conventional lighting and some forms of emergency lighting do not serve any useful guidance purpose. High intensity LED guidance systems offer useful benefits of low power, ruggedness and visibility of around 2 metres. However these systems would be prohibitively expensive for long tunnel applications. Variants of these systems are employed in underground rail and road tunnels to provide emergency lighting and lifeline systems.

7.2.4 Visibility Issues of Emergency Guidance Systems and their Effectiveness in Smoke

Collins (1991) and Collins et al (1990, 1992) undertook a review of the research literature on the visibility of exit signs, directional markings, and emergency lighting. Work was also presented on a study that assessed the visibility of several types of exit sign, including conventional and electro-luminescent, in both clear and smoke conditions. A two-part evaluation was performed. In the first, signs were measured photometrically in clear conditions with two different photometers in a laboratory to determine their luminance under dark conditions and with an ambient room illuminance of ~50 lux. Analysis of the data indicated very wide variations in luminance (from about 0.9 to 1350 cdm^{-2}) as a function of sign type. In the second part of the study, the visibility of the signs in both clear conditions and smoke was assessed psychophysically. A total of 21observers participated in the assessment of visibility. Analysis of the data indicated that overall sign luminance was one of the primary determinants of visibility in smoke conditions, whilst uniformity was also an important contributor. The data indicated that some electro-luminescent signs could be effective in clear conditions and in smoke (particularly if their luminance is above about 10 cdm^{-2}). Consideration of the results indicated that somewhat different characteristics of the signs seemed to determine their visibility for clear conditions than in smoke, with uniformity (or sign configuration) playing a larger role in clear conditions, and luminance being more critical in smoke. Finally, the data indicated the need for further research in which the effects of colour, sign configuration, and luminance are varied parametrically.

Whilst a number of surface emergency guidance technologies have been marketed, according to the UK Building Research Establishment (BRE) (Webber, 1997), there is only one international standard for assessing guidance components in smoke: Underwriters Laboratory standard UL1994 (Underwriters Laboratories, 1994). However, this standard is restricted to a fixed viewing distance, 3.7 metres and smoke of relatively low optical density $0.082m^{-1}$. There is a requirement for standardised assessment methods for evaluating the visibility of guidance components in varying conditions of smoke obscuration. The visibility of exit signs and other illuminated escape route elements in smoke have been shown to vary widely (Webber et al, 2001a; Rea et al, 1985; Collins et al, 1990; Webber and Aizlewood, 1994a/b; Webber 1997).

Observations from tests conducted by Webber et al (2001b) suggest that there may be a negative impact from conventional high-mounted escape route lighting as called for in British Standard 5266 (BS5266, 1998; BS5266, 1999) in terms of walking speed through smoke. In tests simulating a smoke-filled building, the test illumination caused people to walk significantly more slowly than for some of the way-guidance systems tested. Simply increasing the illuminance of an overhead lighting system does not radically increase the speed that people are prepared to walk at. Even under normal lighting conditions, with a minimum of around 20 lux on the floor in clear air (compared to less than 1 lux for the emergency lighting system) people still walk significantly slower than when using dimmer way-guidance systems. The effectiveness of way-guidance systems is not just a factor of the floor illuminance, but also the direction of the viewing of the light sources providing visual cues which outline the escape route and emergency exit doors. Here factors affecting their effectiveness include the photometry of the light track, its orientation and location.

Skjong and Courcoux (2001), reviewing TNO's mustering and evacuation project, describe tests of two guidance systems. The first system was based on a moving sequence of lights (involving sequentially strobing an array of LEDs). The promise of such systems is the possibility to program the direction of evacuation. The guiding effectiveness of the system was tested in normal lighting and a 'power failure' situation. The results were disappointing. Under normal lighting conditions, the system was invisible; in darkness, the system was a nuisance. It failed to improve way-finding behaviour, and during post-test debriefing interviews, very few volunteers mentioned assistance by the system. The second guidance system was based on photo-luminescent low-location-lighting strips with arrowheads added for direction. The approach proved better than both the moving LED prototype system and the traditional system, both with regard to time required and in terms of way-finding errors. Experiments were also carried out with markings on the floor and other structures that may be critical in an emergency. The validity of these test results is limited as they pertain to particular systems and a particular layout of corridors. The systems could be improved, for example, by packing the LEDs more densely. The cost of the system using densely packed LEDs would be quite high and would not be relevant to long arterial tunnels. The second system also has limited relevance. Photo-luminescent materials must be pre-conditioned by a relatively high light flux within a spectrum of 200-450nm (peak excitation occurs at 360nm) and the materials are subject to ageing. Conventional zinc-sulphur compounds need replacement within 3-5 years, with strontium-aluminium compounds required for longer service life.

Within the UK, work by BRE (Webber 1997; Webber and Aizlewood, 1993, 1994a) has shown that light emitting diode (LED) based guidance systems have, in relative terms, high levels of penetration and hence recognition distance. High intensity LED based systems are arguably the best choice set against typical reflective, electro-luminescent, miniature incandescent, photo-luminescent and fluorescent alternatives for intrinsically safe application. Webber and Aizlewood [1994a] cite the relatively high efficiency of LED based systems for smoke optical densities up to $3m^{-1}$. A comparison of the relative visual conspicuity of various generic light source types is given in Figure 7.3.

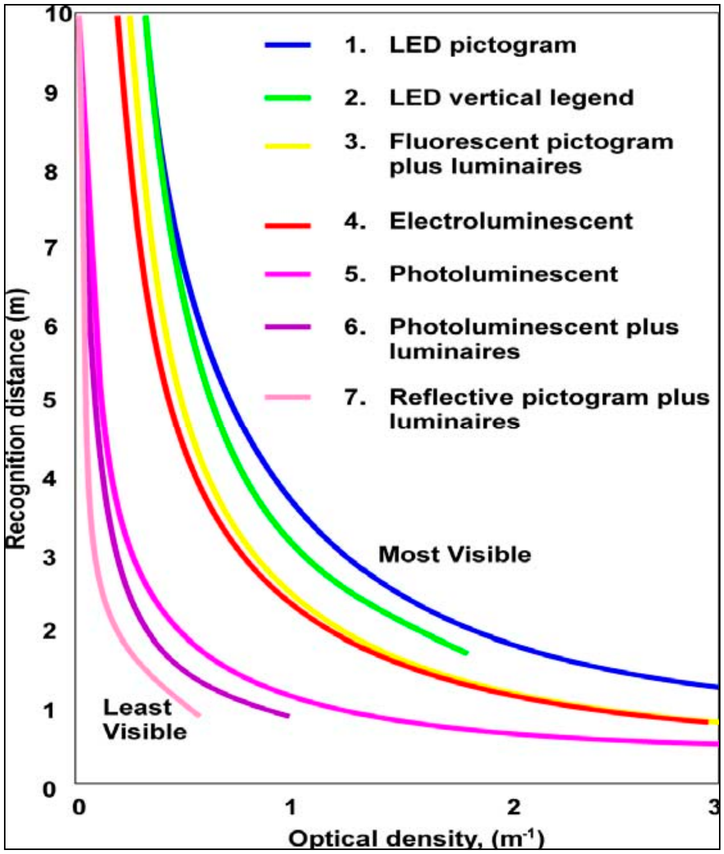


Figure 7.3 : Relative conspicuity of generic light source types in white smoke (after Webber and Aizlewood 1994a)

In extensive trials undertaken by NIOSH (Conti et al 1999; Conti and Chasko 2001), the technologies considered best suited to guidance through smoke were laser lights and lifelines, whilst light vests and person-worn laser lights were ranked best at helping rescue team members identify one-another. Figure 7.4 and 7.5 show the results for each case respectively (Conti and Chasko, 2001).

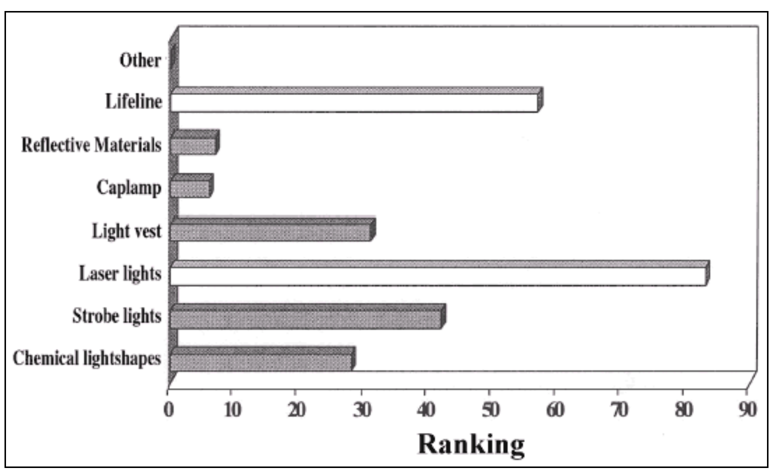


Figure 7.4 : Rating of value of technologies for assisting guidance through smoke (after Conti and Chasko 2001)

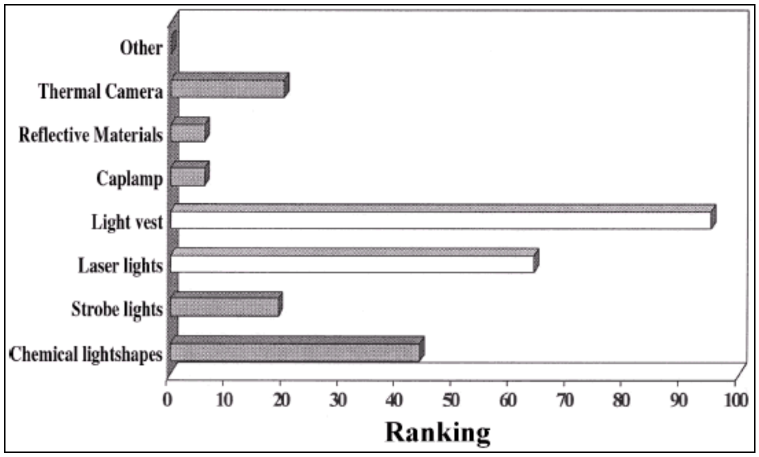


Figure 7.5 : Rating of technologies to help rescue team members identify one-another (after Conti and Chasko 2001)

Further group surveys of experienced rescue staff were conducted to ascertain the best light colour for use in black and white smoke types (from actual fires and simulated sources). In each case, green was the favoured colour, expressed by 85% and 77% of the respondents for black and white smoke types respectively. This is an important finding for evacuation system designers and researchers. The result parallels the CIE photopic (daylight colour vision) relative sensitivity function, V(λ), which confirms a peak sensitivity at 555nm optical wavelength (pure green). The photopic sensitivity function is given in Figure 7.6 below (ICNIRP, 1999). Further consideration is given to conspicuity and relative brightness of light sources in §6.3.3.3 (Beacon Systems Employing High Intensity LED Technology).

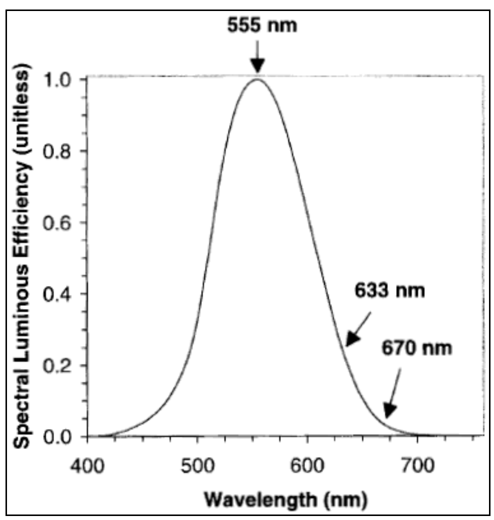


Figure 7.6 : Photopic sensitivity function of the human eye

In general the recognition distance of guidance signs is dependent on a number of parameters (Webber and Aizlewood, 1993; Boer and Skjong, 2001) and it is difficult to develop a general model appropriate to underground circumstances. These parameters include:

- Size and detail
- Use of letters or pictograms
- Luminous and intensity characteristics
- Contrast

- Colour
- Ambient lighting level
- Visual adaptation
- Visual acuity of viewer

One factor for maximum penetration and detection through smoke is that the light should be a point source rather than a planar source (Webber and Aizlewood, 1992). For the collection of guidance system optical source types, relationships can be defined between recognition distance (R) and optical density of the smoke (δ). Data fitting of experimental data gives an equation of the following form (Webber and Aizlewood, 1994b):

$$\delta R = k - m \log_{10} R$$

Where δR is the total optical density, i.e. the product of the recognition distance and optical density of the smoke, and k and m are constants. From this relationship it is possible to extrapolate behaviour from a limited set of test conditions.

It is also of interest to examine empirical data and basic principles for light transmission through atmospheric fog since these are analogous conditions. Simple models of transmittance through the atmosphere assume independence of wavelength throughout the visible portion of the spectrum. The illuminance (E) produced at a distance (x) by a source of luminous intensity (I) in an atmosphere having a transmissivity (transmittance per unit distance) (τ) is defined as:

$$E = I \tau^{x} / x^{2}$$

In clean fogs and rain this is valid. However, in smoke or dust the equations must be applied wavelength by wavelength. Transmissivity and extinction coefficients for dense fog types are given below in Table 7-2 (IES, 1993).

Table 7-2 : Optical transmissivity and extinction coefficients for dense fog

Weather Type	Optical Range, m	Min. Extinction Coeff. per metre	Max. Transmissivity per kilometre
Dense Fog	50	0.06	$9.5. 10^{-27}$
Very Dense Fog	30	0.10	$4.3. 10^{-44}$
Exceptionally Dense Fog	15	0.20	$1.8. 10^{-87}$

These figures show that optical attenuation rates for dense fog are very high. Dense smoke is more attenuating, indicating that it is difficult, with practical IS light sources, to have a visual range much beyond about 10 metres in severe conditions. Further transmissivity modelling, including those involving turbid media are noted by Boyce and Gamliel (1992), Gross (1986, 1987) and Roysam et al (1991). The latter models are important in designing systems to highlight escape hatches in military helicopters, which may 'ditch' and submerge.

7.2.5 Summary of Available Guidance Technologies

The foregoing review of surface and underground guidance technologies may be summarised as follows in terms of relative performance and cost:

- Passive rail and lifeline technologies provide the lowest cost approach to guidance. However, there are limitations, viz.

a) difficulty in providing continuous physical access to a line or handrail;
b) possible directional ambiguity;
c) not self-illuminating or self-revealing;
d) strong tactile reliance.

- Retro-reflective signs have limited value in conditions of very low visibility and may require frequent cleaning. Self-powered emergency lighting strips using light emitting diodes (LEDs) offer benefits of high relative efficiency, robustness and greater brightness compared with incandescent lamps. LED strip lighting has high cost implications.
- Active guidance systems potentially offer an effective response to a variety of incident situations. However, these systems need to be engineered and tested to meet a variety of behavioural, human perception and ergonomic requirements. Any systems must have reasonable acquisition cost, relatively uncomplicated installation and should materially increase evacuation speed even in very low visibility conditions.

7.3 Development of an Evacuation Support System

The development work focussed initially on examining the feasibility and relative merits of various technical approaches. The use of various forms of rope, line or rail mounted on the tunnel wall, to provide tactile direction cues (unidirectional cones or shoulders), is recognised as a valid way-finding assistance approach. However the feasibility of installing mechanical guidance aids, then testing the implementation of such schemes is largely an operational matter for tunnel operators. Handrails and walkways are also specified for new tunnel designs. The research has concentrated on active techniques of way-finding and guidance through smoke. The system design emphasis, apart from its effectiveness in smoke, has been to ensure a high retrofit potential.

The work on developing a proof-of-principle evacuation support system has progressed from a critical analysis of a wide range of way-finding techniques and issues, to encompass design studies on candidate approaches. This work has progressed to include a significant effort on developing and designing prototype hardware. Whilst resources restrict this to a ‘proof-of-principle’ design (in terms of completeness), it is anticipated that the resulting design could be adapted to a wide range of tunnel situations.

During the first year of the UPTUN programme, work included assessments of the following candidate methods:

- Providing audible/visual cues in addition to tactile cues.
- Illuminated line approaches;

  (a) Electro-luminescent ‘Cool Wire’ technologies
  (typically requiring high voltage ac excitation)
  (b) Evanescent mode excitation of fibre optic cables
  (typically requiring >0.5 W semiconductor laser).

- Distributed discreet audio-visual beacon systems, employing;

  (a) Free-field sound localisation
  (b) Sequenced tone systems
  (c) Xenon strobe systems
  (d) High brightness light emitting diodes
  (e) Solid state laser diodes

(f) Combinations of the above

As noted, the first part of the research concentrated on evaluating the problems of evacuation through smoke together with possible means to provide active way-finding assistance. Candidate techniques and associated technologies have been evaluated further and are reported here.

7.3.1 Electro-luminescent Line Technologies

Electro-luminescent line technology has been appraised principally from a standpoint of assessing likely performance and operational issues. Heavy-duty cables can be supplied by ELAM Limited. These are available with phosphors able to produce blue-green, green, yellow, red and white colours. Braided synthetic fibre high-strength ropes with a woven electro-luminescent core are also manufactured by English Braids Limited in the UK. Typical braid forms are shown in Figure 7.7. A design review was undertaken to evaluate the feasibility of driving a long electro-luminescent line at high brightness. The brightness and power consumption characteristic versus frequency and excitation voltage for heavy-duty electro-luminescent cable was determined. High brightness operation requires line voltages typically in excess of 100 V rms and power consumption of ~1 Wm^{-1}. At these power consumption levels, brightness will be of the order of 150 cd m^{-2}. This is a relatively dim light source, but may have utility if the line could be installed at or close to eye level.

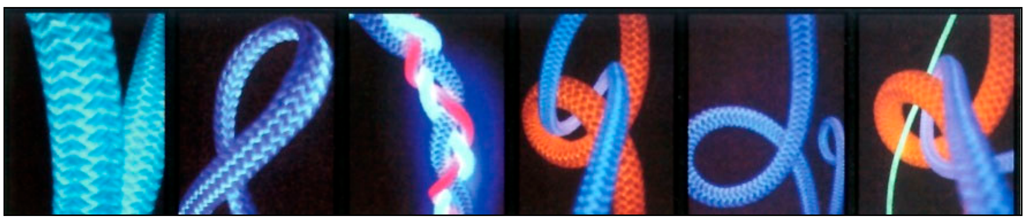


Figure 7.7 : Example high-strength woven ropes with electro-luminescent cores

In assessing this technology, it was noted that measured brightness declines rapidly in the first 500 hours of operation, stabilising at below 30 per cent of reference (initial) brightness after 3500 hours. The inherent stabilisation characteristic for luminous output with elapsed time recommends that a system should not be left permanently energised. Given that electro-luminescent cable members must also remain physically and galvanically intact and be powered for light to be omitted, any system could in practice have questionable integrity, after a fire has developed. A requirement here to improve system survivability and operational integrity, would be to split the line into a multiplicity of segments, each separately powered.

7.3.2 Laser Diode Illuminated Fibre Optic Cable

This approach to way-finding has largely been researched by the Photonics Innovation Centre, School of Physics and Astronomy, St Andrews University Scotland. Early commercial systems have been identified. In concept, the scheme typically requires >0.5 W visible laser light to be injected into the fibre. This is feasible and in principle fibre optic cable lengths of 100 metres or more could be illuminated. Lifor Ltd, an Edinburgh based company, licenses the technology, with the development intended for offshore evacuation and way-finding applications initially. A further commercial offering ‘Intenslite’ has been identified, but no further details could be obtained. Prototype systems have exhibited high brightness along a 500-metre length optical fibre. Major concerns over laser safety and the lack of system integrity in a tunnel fire environment are noted. The fibre optic cable must also remain intact and significant optical power has to be launched into the fibre and its cladding for the scheme to be effective. The optical cable when illuminated, Figure 7.8, has an appearance similar to electro-luminescent cable, albeit potentially somewhat brighter.

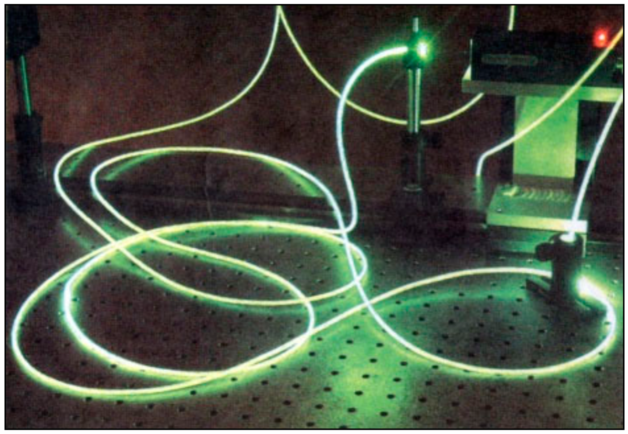


Figure 7.8 : Laser lifeline demonstration system

One interesting development considered was the possibility of incorporating distributed optical fibre temperature sensing within a fibre optic scheme, where spatial resolutions of <0.5m and temperature resolutions of 0.1°C are possible. Within such a system, there is some design freedom to optimise system parameters, viz.; spatial resolution, temperature resolution, total number of separately supported sensing zones, measurement update frequency. This type of system is an emerging method of fire detection in vehicular and rail tunnels. Distributed optical fibre temperature sensing has been demonstrated with fibre optic cable of >5km in length (Willett et al, 1995). A review of distributed temperature sensors by Dobroski and Conti (1991) suggested that such systems have the capability of providing protection over substantial lengths, and are less prone to false alarms.

7.3.3 Audio-visual Beacon Systems

The use of discreet audio-visual beacons, which are provided with a standby battery power supply, is considered the most relevant technology to providing way-finding assistance after a major fire incident underground. The key advantage is that the system can be engineered to be fail-safe, i.e. activated automatically when power is lost. There is thus no requirement for the power supply line to remain intact for the system to operate. A number of conceptual beacon forms were examined, with particular attention being given to producing a low-cost design with good ergonomic performance.

In relatively light smoke obscuration conditions an entirely optical system would suffice. However it is likely in a number of fire incident situations that optical obscuration from products of combustion will greatly restrict visibility. In these circumstances, additional way-finding cues are required, essentially predicated on audible and tactile means. Significant effort must be given in the design to ensuring any system is simple and intuitive to use.

<u>Beacon Systems Using Laser Diodes</u>

A review of research work conducted by the Pittsburgh Research Laboratory of NIOSH identified that solid state lasers may have a useful role in providing guidance through smoke. Accordingly, prototype beacon units were designed which incorporated Class 2 (0.9mW) and Class 3a (4mW) red and green laser diode devices. Regarding laser health and safety, assessment of risk and guidelines on experimentation were drawn up based on accepted safety statements (Revision of the Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 400nm and 1.4μm, Health Physics Vol. 79, No 4, pp 431-440, 2000, and, Light-Emitting Diodes (LEDs) and Laser Diodes: Implications for Hazard Assessment, Health Physics, Vol. 78, No. 6, pp 744-752, 2000). The beacons were installed in an underground gallery at

MRSL's headquarters, which can be filled with white smoke of a controlled density. The prototype housing with two laser modules is shown in Figure 7.9.

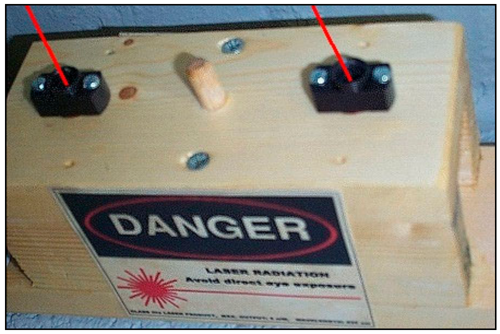


Figure 7.9 : Class 2 (0.9mW) and Class 3a (4mW) red laser modules in test housing.

In trials, the gallery was progressively filled with white smoke and observations made on the way-finding value of the laser paths between the units in various smoke conditions. In 'light' smoke conditions, the laser path was visible for 5-6 metres. However in 'heavy' smoke, visibility was less than 1m from each of the laser light sources. The Class II (0.9mW) lasers were less visible than the Class III (4mW) lasers, and the Class III green laser was slightly more visible than comparable power red lasers. Based on these tests, the use of lasers for way-finding through smoke is rejected and this particular avenue of research would not appear to warrant further investigation.

Beacon Systems Employing Xenon Discharge Tubes

Experimental work was conducted to evaluate the relative merits of adding a xenon discharge tube to the beacon design. The rationale was that higher peak optical power can be delivered, with a commensurately higher emergent flux through smoke. A xenon source also provides isotropic emissions, rather than the highly directional emissions from narrow angle LEDs. However, disadvantages include a lack of directional information, the requirement for high voltages, and high peak battery currents. Nevertheless, a design incorporating a high-power LED direction indicating arrow and a xenon light source was considered feasible.

On testing a range of commercial, battery-powered xenon beacons in a smoke-filled gallery, the value of the beacons was shown, however, to be marginal at best for guidance purposes. In particular, the extremely short duration of the xenon discharge does not allow their relative spatial positioning and direction to be readily gauged. Penetration through smoke was also less than anticipated. On balance, the use of xenon beacons (of any colour) could not be recommended for way-finding through smoke. The beacon types selected were considered to be well-engineered and could not be criticised in themselves. The limitations were considered rather more to be generic limitations of using xenon discharge technology in this application. Examples of the beacons used are identified below in Figure 7.10:

Figure 7.10 : Battery-powered xenon discharge beacons used in gallery tests.

The issues of perception associated with flashing light sources were investigated at an initial level and are discussed below.

Beacon Systems Employing High Intensity LED Technology

In designing a way-finding optical beacon system for use in smoke there are a number of physiological and perception issues which must be considered in addition to the physics of light penetration through scattering media. In particular, we may also be interested in maximising the attention-getting and detection characteristics of the optical signal. These factors are briefly reviewed here. Specific aspects were checked in gallery trials of the prototypes.

Physiological Vision and Perception Issues

The following design options impact on visual performance:

- Choice of colour and size of source
- Spatial resolution (typically involving contrast detection)
- Temporal resolution (typically involving a flickering or flashing source)

The choice of colour will also influence the atmospheric attenuation through a scattering medium. The above issues are relatively complex, but a number of theoretical points can be made concerning the optimisation of the optical arrangement, as follows.

Choice of Colour. Optical scattering is exhibited for a light source penetrating a medium containing high levels of dust or combustion particulates. Classical scattering analysis suggests that the light source should be selected to have the largest practical wavelength, i.e. biased towards the red end of the visible spectrum. A green source will be more severely scattered and attenuated than the red source. However under the anticipated conditions, day (photopic or light-adapted) vision will be effective rather than night (scotopic or dark-adapted) vision. Under these circumstances, the eye has maximum sensitivity to yellow-green light.
The human eye contains two main classes of light-sensitive receptors that are differentiated by their morphology and by peak spectral sensitivity of the photo-pigments that they contain. Rods, which are absent in the fovea, are extremely sensitive to light and have a scotopic peak spectral sensitivity at about 507 nanometres. Cones are located in the centre of the retina and are less sensitive but make possible colour discrimination. Cones have a photopic peak spectral sensitivity at about 550 nanometres. Adaptation also plays a part in that some colour discrimination is retained for adaptation involving the following processes; change in pupil size, neural and transient adaptation. The implication from the above is that under low levels of illuminance, blue lights could be more efficient than green lights. However,

taking into account anticipated lighting levels and scattering behaviour, the best choice of light would be in the green-yellow to red region of the spectrum.

There are some cautionary points to note in the use of small colour-coded lights to provide directional indication. Firstly, studies show that up to ~8% of subjects can exhibit colour-blindness. Partial colour-blindness typically involves confusion between red-green or blue-yellow colours. For this reason, if colour is used for any coding, it is important that additional visual or tactical cues are given to indicate direction, by example incorporating a large raised arrow in the case moulding, or using pictograms. Further to this, if light levels are very low, perhaps caused by failure of local emergency lighting, then colour perception will be poor. In the photo-chromatic interval between rod and cone thresholds no perception of hue can be made (Hill, 1947). Colour perception of small point sources of light is also limited due to small field tritanopia. Offsetting these limitations, there will be effective widening of the light source area in smoky conditions due to scattering. Taken on balance, and the need to obtain maximum smoke penetration, the use of point light sources in the beacon rather than planar sources was considered acceptable.

Flashing Light Signals. To increase the conspicuity of the light sources within the beacon and their apparent brightness, then flashing or flickering light signals may be used to good effect. Flashing lights used as warning devices typically have flash frequencies of the order of 1.0 – 1.2 Hz. For repetitive flashes at frequencies between 2 and 20 Hz, the signal may have supra-threshold brightness greater than that of the same stimulus presented continuously. This is known as brightness enhancement or the Bartley effect (Bartley, 1938). Even single pulses of light may appear brighter than a steady light under some conditions (Projector, 1957).
Accounting for persistence of vision effects, it is possible for a flashing light to have a relatively low on-off ratio. If for example, the flash frequency were 1.0 Hz then the light could be on for ~0.2 seconds and off for 0.8 seconds. This diversity can greatly extend operating battery life, with the mean power consumption reduced to around 20% of a continuously powered light. Where lights cannot be flashed on and off then flicker modulation may be used to increase attention-grabbing characteristics. Subjective sensitivity to flicker is broadly maximised in the 6 -10 Hz region (Kelly, 1969). In the given application both flashing and flickering configurations have been examined and each approach was considered effective.

The choice of light source is essentially limited to light emitting diodes (LEDs). It was recognised from the outset that best available LED technology would be required. A device specification of >10,000 mcd luminous intensity was judged necessary to obtain sufficient smoke penetration. The devices would also have to offer good reliability when operated in a high current pulsed mode, with a peak current close to the absolute maximum rated pulse forward current, IFP for the device.

The selection of a red device presents relatively few problems, since aluminium indium gallium arsenide (Al In Ga P) LED technology provides luminous intensities >15,000 mcd with a typical viewing angle of 8º to 10º at a dominant wavelength of ~625 nanometres. There is clearly a trade-off between viewing angle and forward luminous intensity. For the application in question, devices offering a viewing angle between the 8º and 15º were considered appropriate.

The selection of a suitable green device was more problematic, since whilst green single quantum well gallium indium nitride (Ga In N) devices with luminous intensities of >6,000 mcd at 525 nanometres are available, they are characterised by a relatively high forward voltage characteristic. These devices also have a relatively low peak forward current capability and are static sensitive. Appropriate circuit design and handling precautions have to be introduced to ensure acceptable device reliability. Checks confirmed that device relative luminosity should not deteriorate in the first 10,000 hours of operation and that a pulsed method of operation is permissible providing the LED die is adequately cooled. For simplicity and reduced cost, the prototype beacons used high efficiency red LED technology. The use of very high output power/efficiency LED technology, such as devices manufactured by Luxeon Inc., and as shown in

Figure 7.11, would permit further gains in visible range of the beacon (albeit that a higher capacity internal battery would also be required).

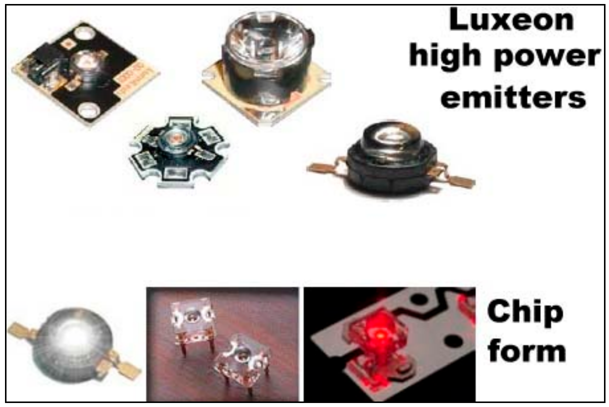


Figure 7.11 : Examples of high output power, high efficiency LED technology

A number of conceptual schemes for an audio-visual evacuation beacon system were investigated. The initial approach incorporated fixed direction, high intensity light emitting diodes (LEDs), within a beacon attached to the tunnel wall. In a linear tunnel situation this provides the evacuee with consistent direction of travel information. Initial evaluation of the scheme ergonomics with a small subject group confirmed that this arrangement would suffice in a simple tunnel situation. Improvements to the ergonomics of the beacon were obtained by configuring an array of LEDs to provide a large, distinctive flashing direction arrow within each beacon, which are then spaced at regular intervals. This should be appropriate to areas where there is complex decision-making.

Whilst a beacon with a flash rate of ~2Hz has high conspicuity, it was observed in trials using dense smoke, that the duration of the beacon flash was important. Essentially, the beacon duty should maintain a high on-off duty factor. For the prototype LED beacon, an on-off ratio of ~7:3 was judged to be a reasonable compromise for assisting guidance through smoke. This clearly has implications for beacon power consumption and hence battery life. The frequency, duration and colour content of a flashing beacon, and its value for guidance through dense smoke requires further systematic research.

<u>Audible Localisation of Beacons</u>

In an emergency, spatial cues on the location of the next beacon could be critical towards maintaining a predictable evacuation travel rate in very low visibility conditions. Investigations were undertaken to establish whether additional directional cues could be provided by inter-unit audio tones or via shaped white noise free field sound localisation techniques. This was considered necessary to respond to the situation where visibility is extremely low and total obscuration of the beacon LED light will occur within 1- 2 metres. Inter-unit tone sequencing was ruled out on the grounds of complexity and cost, in that synchronised precision electronic clocks would need to be maintained within each beacon unit.

Investigation of single transducer sound localisation technology has been conducted, based on research and technology developed and commercialised by University of Leeds/Sound Alert Technology Limited. The use of amplitude and frequency shaped broadband noise is considered to provide an effective localisation capability in nil visibility conditions. This approach has merit, albeit that the beacon must be equipped with a relatively high capacity battery and the localisation is sensitive to the bandwidth extension of the acoustic transducer. Further work suggested the need to provide a broadband tonal signature to permit free field localisation of a single acoustic source. Investigation also confirms the need to have significant low-frequency spectral content to provide efficient localisation. Accordingly, this aspect was examined further. The constraints of providing an appropriate acoustic source in terms of the current beacon design are as follows:

- The relatively small enclosure size limits the size available for an acoustic transducer.
- A high acoustic cut-off frequency is imposed by a small enclosure.
- The low overall acoustic efficiency places a heavy burden on the small internal rechargeable battery.

After relevant experimentation, it was concluded that the provision of a broadband acoustic transducer would not be feasible in the current design. A compromise involves using a band-limited transducer driven by a pulsed noise source derived from a pseudo binary sequence generator. This was initially undertaken in hardware, but subsequently via software.

One important area of related research is TNO's work on acoustic localisation, and instruction and guidance of naive subjects through smoke (Boer and van Wijngaarden, 2004). This important study has assessed the feasibility of acoustic localisation in smoke-filled tunnels using polytone signals and speech fragments. Part of the studies included examining the feasibility of incorporating a broadband noise-based acoustic localisation feature. Previous research into localisation of sound using broadband noise has lead to a number of patents being granted on behalf of Sound Alert Limited, Leeds UK. One patent cited is US Patent No. 6,201,470, which makes the following (principal) claims:

- A directing and alerting device which is adapted to emit either simultaneously or successively a locating sound comprising broad band noise formed from frequencies emitted simultaneously and falling within a human hearing range between 40 Hz and 20 kHz; and an alerting sound comprising at least one frequency within the human hearing range.
- A device according to claim 1 wherein said locating sound comprises white noise or a flat random noise.
- A device according to claim 1 wherein said locating sound comprises at lease one selected frequency which is either amplified or attenuated.
- A device according to claim 1 wherein said locating and alerting sounds are emitted successively.
- A device according to claim 4 wherein there is a predetermined interval between said emissions.

Apart from patent and possible licence restrictions, the authors perceived some difficulties in incorporating a white noise signal or broadband noise, capable of generating appropriate sound levels in the range 40 Hz to 4 kHz (as indicated by the above patent) within the small enclosure and limited power levels available within the prototype beacon design. The findings of Boer's and van Wijngaarden's work suggest efficient localisation is still possible without the transducer bandwidth suggested for broadband (white) noise localisation. This potentially provides significant engineering benefits in terms of transducer and beacon enclosure size, power consumption and cost of implementation. The approach adopted by Boer and van Wijngaarden has been experimentally verified, and the suite of acoustic localisation techniques developed by TNO reflects a comprehensive understanding of the tunnel acoustic environment and the research field of psycho-acoustics and localisation. One observed technique, for example, is to insert a 5-10 ms amplitude transition on the leading and trailing part of the signal segments to reduce 'overhang' in reverberant built structures.

The structure of a mixed speech plus polytonal tunnel 'Exit Here' instruction used by Boer and van Wijngaarden is discussed further, as follows. It is desirable that acoustic-based instruction and way-finding beacons do not hinder any PA announcements, which is at variance with beacons that use speech. To improve the intelligibility of tunnel verbal communications, 50% silence was inserted between the sound sequences of the beacons. Further to this, in order to enhance resistance (reduce masking) from environmental noises such as ventilator sounds, a sound spectrum was chosen that differed as much as possible from predictable tunnel sounds. The sound selected was a succession of two complex tones each with two basic frequencies (the tones 'C' plus 'E', followed by 'E' plus 'G'). All harmonics of both basic frequencies were included in the signal up to 18 kHz. The speech fragments also received special processing to ensure maximum localizability. It is generally accepted that consonants are the key to speech intelligibility, which can be improved by:

- Designing a rising frequency response to enhance consonants.
- Ensuring a wide enough bandwidth to cover the sound spectrum of consonants.
- Incorporating filtering that boosts the level of the quieter consonants whilst leaving vowels unaltered.

Figure 7.12 shows the main characteristics of the polytonal sequence (from Boer and van Wijngaarden, 2004)

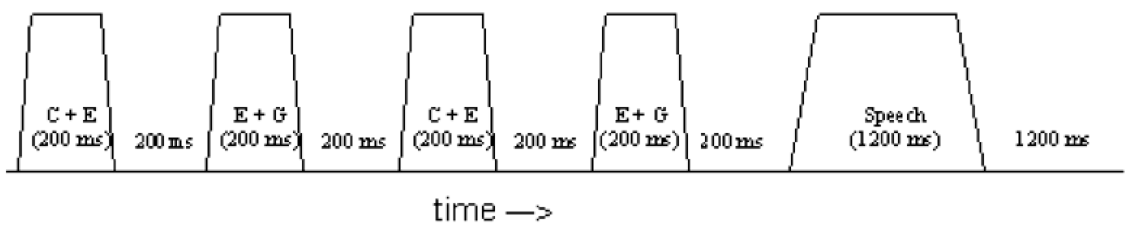


Figure 7.12 : Polytonal sequence possessing localisation and attention-gaining qualities

It is noted that factors contributing to human sound localisation capacity are not yet fully understood. Early research examined localisation of pure tone bursts. Differences in localisation acuity were explained by the existence of ‘interaural timing differences’ (ITD’s) at low frequencies and ‘interaural level differences’ (IID’s) at high frequencies. These timing and level differences between the two ears of the incident wavefront form part of the fundamental framework of directional hearing cues. The pinnae (or outer ears) are also known to play a part in the localisation of sound. They are considered to be most important when judging the elevation of a sound source. Since then, studies have focused more upon the spectral transformations of the sound that are caused by the pinnae and less upon time delays. Studies have established the pinna as a direction dependent filter that causes spectral changes that can be used as a cue to the location of a sound source. Individual ‘head-related transfer functions’ (HRTF’s) have been created by measuring the spectral characteristics of sounds arriving at the subjects’ left and right ears from a range of locations, and these are a high fidelity means of simulating real sounds. Apart from physiological contributions to localisation accuracy, such as pinna effects and stimulus frequency, there are also methodological factors at work, such as head tracking and facing sound sources. It is evident that a number of variables are involved in the localisation process and that the precise role and contribution of any of these factors remains to be resolved. A selection of references on sound localisation are given by Carlile and King (1993), Haas and Edworthy (1996), Makous and Middlebrooks (1990), Rutherford (1997), Searle et al (1976), Stevens and Newman (1936), Wenzel et al (1993), Wightman and Kistler (1993), Withington (1999, 2000, 2001), and Wright et al (1974).

7.3.4 Introduction to Beacon, Power Supply and Telemetry Scheme

A simple-to-install evacuation support system has been developed with some unique features, including the use of a single wire to provide power in a contact-less fashion to each beacon via inductive power transfer. This should avoid the overhead of local power supplies and the cabling and multi-pole connector problems associated with conventional approaches. The system design offers fail-safe behaviour, with each beacon activated when the electrical charge line is broken or de-energised. The benefits of contact-less operation include galvanic isolation of individual units, guaranteed charge current sharing, the possibility of meeting high environmental protection standards and simplicity of installation. The charging circuit has been confirmed to operate in a stable and predictable manner. A lumped parameter model was developed for the charging line.

The same single wire is being used for command telemetry purposes, where the direction assignment of each beacon can be changed remotely and sensor data can be telemetered back to a central unit. This offers a capability to monitor environmental conditions at each beacon and to reassign the evacuation route. It should also be possible, in principle, to dynamically reassign escape direction in response to incident conditions, although this aspect requires further research. The arrangement of the charging line and toroidal inductors for power transfer and telemetry can be gauged from Figure 7.13.

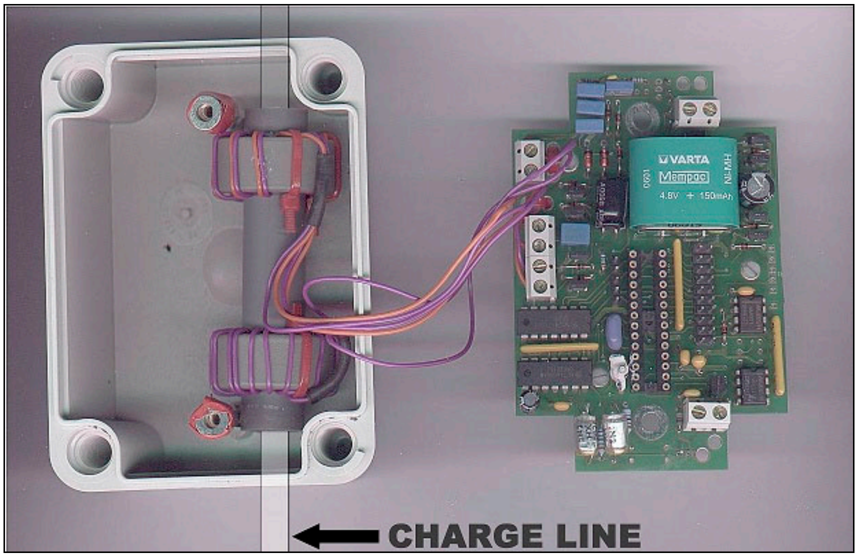


Figure 7.13 : Early prototype showing control board and power/signal transfer inductors

The development work has progressed in two phases, as follows:

- The basic unit uses fixed direction high intensity light emitting diodes, configured as a highly visible flashing arrow. This system is used where there is a fixed evacuation route and offers 1.5 hours operating life once activated. The units can be equipped with a sounder unit to aid localisation in heavy smoke conditions.
- The programmable system incorporates addressability and remote control of the arrow direction. The units can have their direction reassigned individually or in blocks (for example to match tunnel ventilation sections). Further built-in beacon facilities include the ability to provide short-term power to an internal sensor. The beacon operating in its various modes is shown in Figure 7.14

Figure 7.14 : Prototype beacon, quiescent and arrow programmed in each direction

The high frequency inductive charging scheme has an optimal operating frequency of 3 – 4kHz. Whilst the charging scheme design was technically straightforward, the inductive telemetry scheme has required significant development input. The telemetry to the beacons (outstations) is accomplished by amplitude shift keyed modulation of the charge current. To minimise component numbers and cost, each unit employs a low power microprocessor. The command telemetry function (central station to units) uses an efficient protocol to offset the inherently low broadcast data rate capability. Return telemetry from the beacons uses an inductive transmission scheme operating at 20kHz – 30kHz. It is concluded that it is feasible to use a distributed contact-less single wire arrangement to provide power and data/command telemetry to a string of electronic evacuation guidance units.

Further development work included the incorporation of a local environmental monitoring capability within the system. In this case, continuous monitoring of local carbon monoxide and tunnel temperatures was incorporated. Information on the selection and testing of the carbon monoxide detector is given in 7.5 (Selection and Testing of Carbon Monoxide Sensor). These measures provide a system that not only meets its primary evacuation support function, but also provides a valuable distributed fire detection and incident monitoring capability. Further investigation is required to determine whether the system can be adapted to provide an emergency annunciation capability. Extensive consideration was also given to various operational and safety measures. This included protocols for programmable direction assignment of devices, automatic triggering methods, and system alarm management and error handling. In the latter case, it is important not to induce ‘cognitive overload’ of operators in an emergency situation. Methods of information presentation and control interaction requirements with tunnel operator staff are recognised to be of critical importance here. Some of the ergonomic and cognitive issues associated with the design and use of this type of system are acknowledged to be complex and require further consideration. Finally, an important aspect of the work programme has involved investigation of system behaviour in representative (smoke-filled) conditions.

The design and engineering aspects of this scheme are presented in Appendix 9 in the form of a ‘product data sheet’

7.4 Recap on Human Behavioural Issues in Tunnel Evacuation

In conjunction with the design and development work on an evacuation system, the observations and conclusions drawn from the literature review on human behaviour were carefully appraised. The intention here was to help establish a cardinal point specification for an evacuation support system. A number of important behavioural and ergonomic issues potentially impact on system design. Some of these are noted as follows.

There is an increasing body of research interest concerned with human behaviour in fire. A relevant international symposium was held in 2001 at the Massachusetts Institute of Technology (Interscience Communications, 2001). Much of the following discussion is attributed to Boer and Skjong (2001), which has been added to in reports submitted to WP3.

The first challenge for orderly and effective emergency evacuation is to make tunnel users/passengers aware of the emergency. Even in the face of disaster, they may collectively ignore the signs or assume an exercise is in progress and continue their normal behaviour. Authoritative guidance is imperative in this phase. In order to reinforce the perceived need for passengers to respond, guidance needs to come from two or more independent corroborating sources, for example, from a public address (PA) system followed by the appearance of a uniformed employee taking control. Passengers are likely to be completely unprepared for an emergency and are likely to miss significant parts of the initial announcements. Proulx et al (1999) cite a building evacuation exercise where 72% of the occupants failed to recall the contents of the announcements. Visual alert messages and announcements from a PA system need to be authoritative, straightforward and intuitive. Repetition of the announcement will probably be required in other languages to reach passengers of different nations. In general, informative voice warning systems can play a significant role in reducing pre-movement times. Grace (2001) describes the fundamentals of human behaviour associated with the initial phase of evacuation and the influence of voice alarm systems.

The second source of guidance may come from tunnel employees, police or emergency service workers appearing at the scene. Until this additional source of guidance arrives, prompts may come only from seeing some fellow passengers leaving their places and evacuating. This hesitancy may result in a delay of several minutes because without direction, tunnel occupants will probably not act immediately to spoken announcements or messages. Boer (2002b) provides a summary of a study commissioned by the Dutch Civil Engineering Division of the Department of Public Works and Water Management (Centre for Tunnel Safety) to investigate the reluctance to accept the emergency situation in a road tunnel test. Drivers were brought to a halt behind a truck that was releasing smoke, and no instruction was provided for five minutes. The test site is shown in **Figure 6.15**. Most tests revealed that drivers took no action at all during this period. In the main, they waited for the traffic congestion to clear while an increasing amount of smoke dispersed throughout the tunnel. An example of comments made was that “no-one else did anything”.

After the first passengers decide to depart, there is a rapid build-up in a follow-on response. There may be further hesitancy in using emergency exits until others have shown that these can be used safely and without recrimination. The behavioural problem identified by Boer (2002b) and Boer and Skjong (2001) is that escape routes are intended for emergency use only and access is prohibited under normal circumstances. This marks them out as ‘no-go’ areas and associates them with potential trespass and reprimand, leading to a reluctance to use the facilities except in clear, unambiguous circumstances. These studies have prompted a requirement for improvement in the design of tunnels for road traffic. In a separate project, partly funded by the European Commission, TNO Human Factor Research Institute have studied how escape doors can be optimally marked for the general, unprepared public. Follow-up studies are addressing the problem of finding escape doors when smoke obscuration reduces visibility to less than a few metres. It has been determined that appropriate marking of escape doors can contribute to evacuation safety.

Figure 7.15 : Tunnel test site to investigate reluctance to accept emergency situations (after Boer 2002b)

After passengers are alert and fully aware of the emergency, they may pursue short-term private aims before they assemble or progress to an exit. Relevant factors are ‘group binding’ and ‘property binding’. Group binding, or the care for family or friends, means that passengers search for others or assemble the group before evacuating. Feinberg and Johnson (2001) review the fatality risks from group-saving strategies. Property binding means that passengers retrieve or secure their possessions. These bindings create a counter-flow of passengers, and slow down the mustering or evacuation process. Retrieving property can result in passengers carrying belongings such as bulky luggage, which claims space and impedes evacuation progress.

Software simulations of evacuations and guidelines for the estimation of evacuation time generally assume that passengers follow the intended route without hesitation or error. Depending on the range of options available, this may not be realistic. In practice, tunnel occupants along with occupants of ferries or buildings, will benefit from instruction and guidance. This instruction is best received from emergency services staff or tunnel operator staff as appropriate. Uniforms are an essential aspect of staff recognition. Whilst it is a planned support procedure to station crewmembers at strategic locations on a ship during an emergency, this is unlikely to be feasible in a tunnel environment. Even then, these procedures may not be possible in real evacuations, as opposed to evacuation exercises. In an emergency incident there is likely to be a 'chaos-stage' where there is incomplete knowledge of the problem, the speed of further escalation, or the amount of time left for evacuation. Boer and Skjong (2001) identify that extra time will be required to respond to a chaotic situation. An IMO paper (ICCL, 2000) reported that times required to muster passengers at assembly points recorded in real incidents (7 evacuations on 6 different ships) were twice those observed in comparable exercises (36 evacuations on 14 different ships).

Way-finding problems are one of the reasons for slow evacuation. Without verbal instruction, tunnel users and passengers need to evacuate on the basis of signs alone. Not all signs have been standardised, and some signs can be improved to aid human visual perception, particularly as smoke builds up. Direction arrow visibility in smoke is highly dependent on shape and line clarity. Further TNO investigations on how individuals find their way to assembly stations using signs (Boer et al, 1993) confirmed a doubling of the time required to complete the route compared with normal walking time. The conclusion reached was that existing signs provide an inadequate level of guidance. Considering that evacuation routes may present multiple decision points, the probability of error-free way-finding reduces as a function of the number of opportunities for way-finding decision errors. The design of the evacuation pathway must eliminate or minimise the number of decision points. The way-finding performance of an individual is related to the cognitive map established by the person. The associated metrics are imprecise, and conceptual models are being developed to handle the information processing associated with the way-finding process (Lo et al, 2001).

In ship experiments conducted by Boer (1998), signs were again cited as providing inadequate guidance. Related causes of way-finding error were considered to be both visual and psychological. Factors related to human visual perception include:

- Some symbols can be improved for better human visual perception, particularly in smoke conditions. Poor visual conditions can reduce signs to meaningless, illegible symbols.
- Signs can be placed poorly, introducing potential confusion. Consistent guidelines are required for the placement and use of the signs.
- Signs may not be readily discerned against a background of advertisements and other information. The visual conspicuity of signs may also be low in the first place. Warning signs should use luminescent materials and other techniques to differentiate and increase attention-getting qualities.
- Signs can potentially provide an ambiguous message with other signs. The use of signing needs to be examined as an ensemble effect.

Psychological causes of way-finding error include reluctance to go through (unknown) doors, or a preference for open areas; and a preference for the familiar. Doors may be psychologically perceived as leading to potential danger, confinement, or resulting in reprimand (Edelman et al, 1980). A cause of way-finding error is the psychological conflict between normal use and emergency use. Doors should be designed in such a way that evacuees can see that there is no danger behind the door, e.g. by using portholes. The design of firedoors should be such that entrants can perceive the door and frame, and confirm that manual opening is possible.

Boer and Skjong (2001) observed that systematic assessment, review and modification of designated evacuation routes enables improvement of passenger flow. However, there is currently a lack of systematic assessment of potential improvements. It is noted that both exercises and software simulations provide optimistic predictions of occupant response modelling and occupant flow in emergencies. Carefully designed human factor research may be required to provide further design data. The effective inclusion of human factors in evacuation planning requires consideration of factors such as awareness time, group binding, and way-finding error potential. This process requires data that is currently unavailable. At least as far as ships are concerned, measures to promote fast and orderly assembly of passengers are considered to include:

- Authoritative and clear announcements public address systems.
- Authoritative and clear guidance from crew to the passengers.
- Ensuring crewmembers are clearly recognisable by means of uniforms.
- Assembly symbols should be optimised for human visual perception.
- Placement of assembly signs should be improved and made against standard guidelines.
- Conspicuity of assembly symbols can be enhanced by reducing ‘attention competition’ from other signs and advertisements.
- Assembly routes should have as few decision points as possible.
- If the assembly route has to include doors, measures should be taken to address door-opening apprehension.
- Fire/emergency doors should be clearly recognisable as such by the (lay) public. The possibility of manual opening should be indicated.
- Assembly routes should not lead through areas that are normally inaccessible (in the view of the public).

A further important issue is the ability to accommodate the visually impaired group within the built environment. By way of example, contrast sensitivity and acuity play a part in 3 out of 5 of the most common visual disorders in the UK (and probably elsewhere in the EU). Vivekananda-Schmidt (2001) has reviewed the issues associated with the visually impaired and has determined that impaired acuity does not affect speed of movement whilst contrast sensitivity does. System planners and designers must take this and other factors into consideration.

7.5 Selection and Testing of Carbon Monoxide Sensor

In consideration of the literature, there appears to be no single optimal class of fire sensor or alarm algorithm. In practice, fire detection systems are considered against application (e.g. industrial, domestic etc) and the relative priorities of detection sensitivity/shorter fire alarm times and nuisance alarm immunity. Combinatorial sensor algorithms are generally used to reduce problems from non-fire aerosols. To arrive at improvements in alarm response time, multiple parameter detection may be required. Fire signatures are generally described in terms of light obscuration, spectroscopy, image processing, zonal or source temperature, CO CO2 or O2 concentration, and products of combustion signals arising from metal oxide and odour sensors, and possibly acoustic emissions. Conventional fire sensors often utilise light scattering or smoke ionisation measurement.

In spite of the fact that there are interference sources of carbon monoxide underground, and that there are fire sources which produce very small changes in the measured CO concentration (e.g. smouldering PVC cables), a decision was made to incorporate CO detection within the beacon outstation. CO is still considered a useful fire signature, and is the causative agent/dominant toxicant in a majority of fire deaths. Furthermore, whilst CO formation associated with non-stoichiometric burning, pyrolysis and fires in enclosed spaces is complicated, there is reasonable historical confidence in CO as a mine fire predictor. The system, by virtue of the number of beacons, would effectively provide a linear array of point measurements. Statistical processing of such data would also be feasible.

After examination of available low-cost CO sensors, and review of reliability studies, a decision was made to base the design on the Monox Compact S type electrochemical sensor. The UK HSE sponsored a joint industry project to examine long-term reliability of low cost CO detectors (Advantica Technologies Ltd., 2001). This particular sensor appeared to offer excellent long-term stability, together with an in-built electrode self-test function (via the internal generation of a fixed amount of hydrogen at the cell active area associated with the application of a specific coulombic charge). The physical outline of the sensor and the typical self-test response are given in Figure 7.16 and Figure 7.17 (below) respectively. The long-term stability and baseline temperature sensitivity of the sensor are given in Figure 7.18 and Figure 7.19. The high accuracy temperature sensor incorporated in the beacon provides a signal for any temperature correction required. Much of the mechanical detail design work was associated with sourcing gas permeable films to the cell sensing ports compatible with minimum response time and adequate environmental protection. Specialised circuitry also had to be developed to permit operation at low voltage and current consumption levels.

A series of gallery trials of approved underground smoke detectors and untried, generic fire detector types was undertaken during 2003 by the UK Health and Safety Executive's Health and Safety Laboratory in conjunction with UK Coal Mining Limited and interested suppliers. MRSL participated in these trials, specifically to evaluate the behaviour the low cost CO sensor. The main exhaust fan, adjusted for the experiments by use of a bypass air door, provided the tunnel ventilation. A diesel locomotive provided contaminating diesel exhaust fumes for the tests.

All of the gallery tests were small scale. The heat release rates from the incipient stage fires were, in general, very low. Equally, the concentrations of carbon monoxide in the downstream products of combustion were also noted to be very low, typically no more than a few parts per million under the prevailing ventilation conditions. An example of the output from two of the trial electrochemical sensors is given in Figure 7.20 below. In the first part of this test, the various superimpositions on background CO level from exercising the diesel engine can be observed. The recorded downstream roadway concentration of CO did not exceed 8 ppm, reflecting the dilution from the small-scale fire source. In developed tunnel fire situations, considerably higher concentrations would be measured.

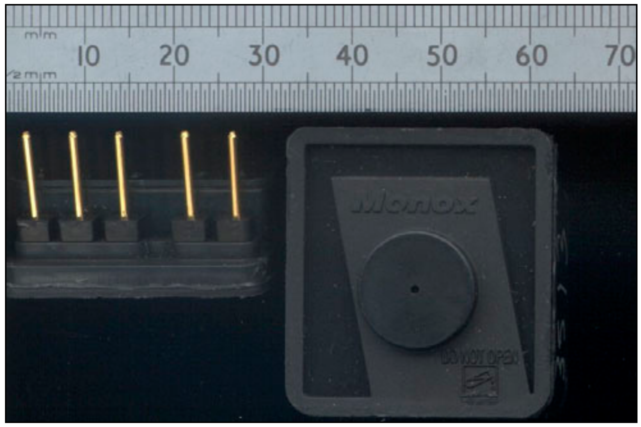


Figure 7.16 : Low cost, high stability CO sensor used in prototype detector

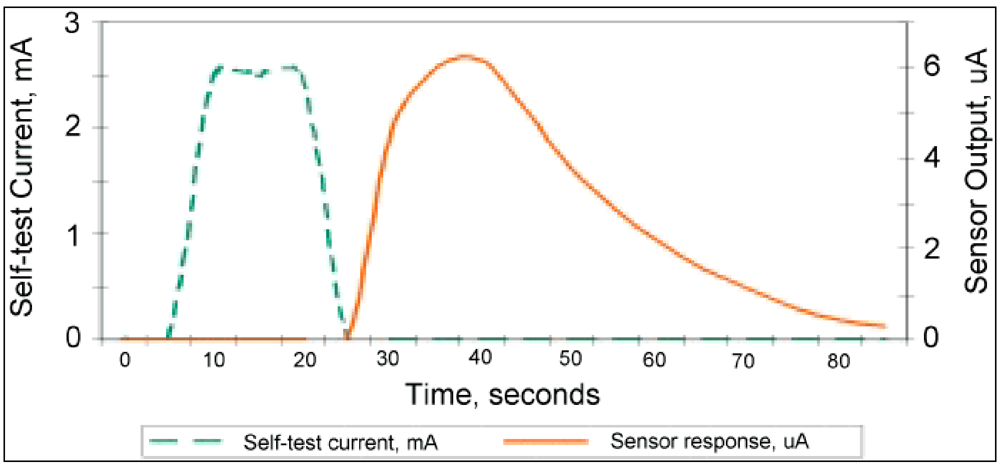


Figure 7.17 : Typical self-test response of CO sensor

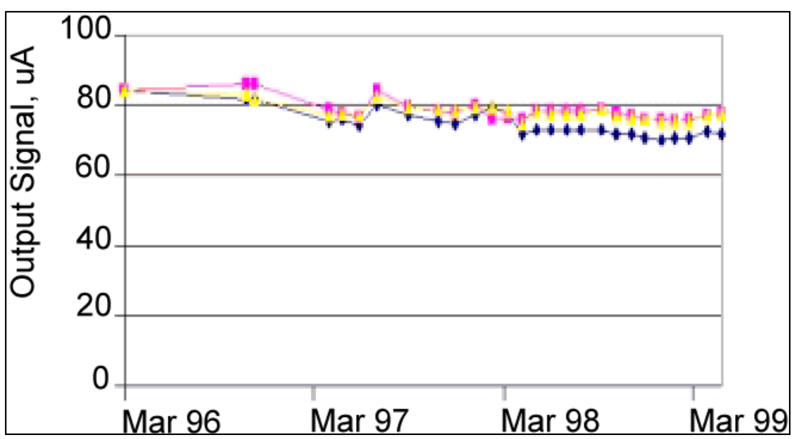


Figure 7.18 : Long-term stability of CO sensor (manufacturer’s data)

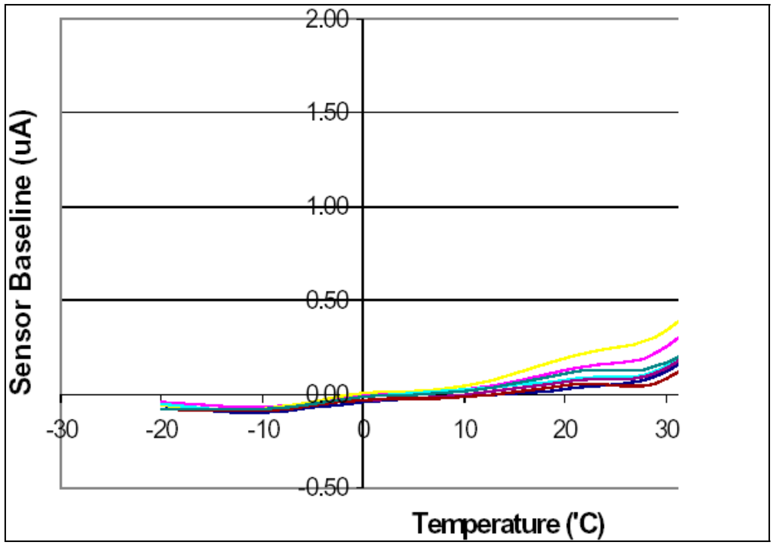


Figure 7.19 : Baseline stability of CO sensor against temperature (manufacturer's data)

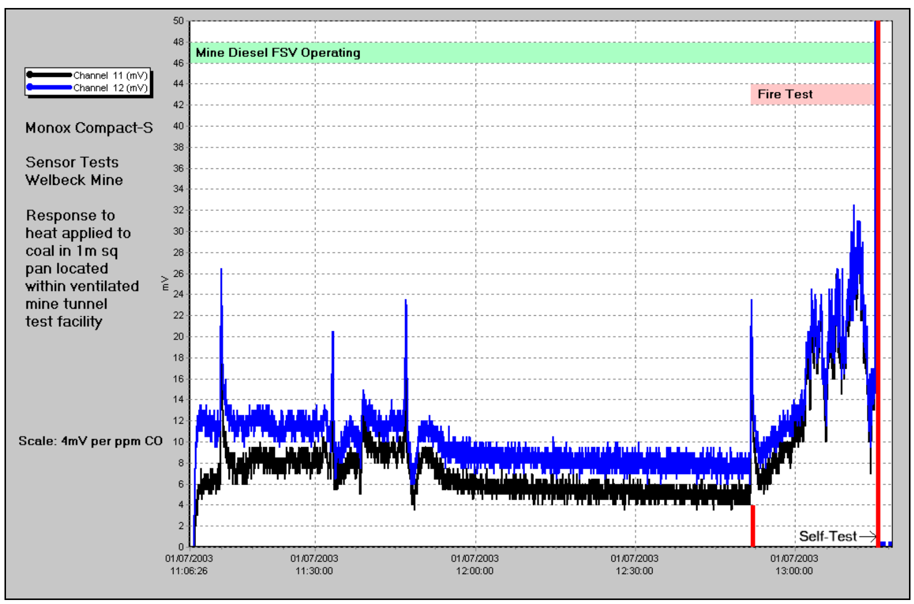


Figure 7.20 : Monox CO sensor signals from diesel/coal fuel test fire

7.6 Concluding Remarks

Within any tunnel safety system design, there is a 'cascade' of steps by importance:

- Prevention of accidents
- Mitigation of incident impacts
- Provide a 'fair chance' of escape
- Facilitate rescue by third parties

The principal research objective has been to investigate and develop a proof-of-principle system to aid guidance and evacuation through smoke, and hence provide at least a fair chance of self-escape. Any evacuation support system must in this regard:

- Significantly increase speed of egress.
- Be useful in conditions of low visibility.
- Present unambiguous directional information.
- Make use of visual, audible and tactile cues.
- Be intuitive, with no prior training or exposure expected.
- Accommodate differences in layout, culture and language.
- Possess high integrity, preferably fail-safe operation.
- Not rely on tunnel lighting and power being present.

Such a support system would be inevitably responding to low frequency, high severity events and it must be assumed that:

- All or most tunnel occupants will lack emergency experience and preparedness.
- Delays in emergency response and initiation of an evacuation could well be significant.
- That this could impact on available residence time to evacuate before reaching critical toxicity and thermal tolerance limits.
- Within a developed fire situation, disorientation, panic and widely varying behaviour can be anticipated.

Further to the above requirements, the ability to initiate or reinforce the initial evacuation response could be useful. The prototype system attempts to address several of these requirements; the system provides useful visual and audible cues, it employs a well-defined indicating 'arrow' for directional information, each beacon has an independent internal battery power supply, and the system has fail-safe activation.

On balance, it was considered that the future introduction of tunnel evacuation support systems, unless prescribed by legislation, would very much depend on system standardisation, system effectiveness and minimising costs of ownership. To this end, building in added-value functions, such as a fire detection and environmental monitoring capability, was perceived to increase the likelihood of take-up. Hence a key decision was made that the system should support dual roles of way-finding and guidance support through smoke, together with providing a multipoint tunnel environmental monitoring and fire detection capability. The system was also to be independently powered, easy to install, have modest maintenance requirements, be of fail-safe design, and have low cost of ownership.

The research has involved a wide-ranging review of behavioural, human factor and physiological issues associated with evacuation. Paragraph 7.4 (Recap on Human Behavioural Issues in Tunnel Evacuation) provides a brief recap on behavioural issues, but it is noted that far more extensive research material is presented elsewhere within UPTUN Workpackage 3. A major area of review involved orientation, vision and guidance technologies, and assessing the relative value of various guidance methods. This included acoustic, visual and tactile methods, offering both continuous or discrete guidance aids. The emphasis was on optical way-finding methods research, although in nil visibility, sound localisation techniques are important. Other issues considered alongside the various guidance methods have included costs and feasibility of retrofit, fitness for purpose, and anticipated occupant - system behaviour.

Against the various way-finding techniques assessed, the following observations and conclusions can be made:

- Walkways with 'passive' life-line or handrails provide a low cost but effective guidance option. Installation of these should be considered as a high priority.

- Self-powered LED strip lighting has high cost implications and was discounted.

- Illumination methods have a varying ability to meet normal (unobscured) conditions and conditions of optical obscuration from smoke.
- Distributed techniques such as electro-luminescent conductors and optical fibre lighting are not fail-safe, i.e. once the cable is broken, illumination is lost. They also have a limited smoke penetration capability. Laser light visibility is also greatly affected by smoke.

BRE (UK) and other test data suggested that high intensity LED (light emitting diode) pictograms could be useful. A large direction arrow was used in the prototype system. In the system development stage, TNO work on arrow visibility was taken into account along with observations from mining and other hazardous industries. The scope to use future ‘ultra-high brightness’ LED technology for increased smoke penetration and visibility was taken into account along with provision of speech and other auditory signal support. The system incorporates an inbuilt dual-range CO sensor for fire detection and subsequent irrespirable atmosphere exposure monitoring of tunnel occupants. Precision temperature sensing was also incorporated to facilitate monitoring and assessment of the local environment regarding heat exposure of rescuers and evacuating personnel.

Development of the highly innovative contact-less, single-wire, inductive charging and telemetry scheme involved a significant research overhead. However, this was justified by the major installation and reliability benefits that would be gained by this approach. High standards of engineering design have been used, including the use of dedicated, low power, RISC-based microprocessors and reliability-centred software development techniques. These are considered essential to any safety-critical tunnel system. Equally, application flexibility has been accorded a high priority, and the system software should accommodate variations in tunnel scale and design.

The specific design features of the system can be summarised as follows. Each beacon is independently powered by an internal battery that is inductively charged from a line carrying a high frequency current, which couples in a contact-less fashion through each unit. There are no direct connections, each unit is isolated and significant cost and reliability benefits are anticipated from not having to use multicore cables and multipole connectors in the system. The single charging line, which can be kilometres in length, is also used to send and receive commands from individual units or groups of beacons. This provides a real-time facility to monitor environmental conditions and call alerts at each beacon, together with (potentially) a capacity to update direction information, responding to the development of a fire. Each unit is fitted with a precision temperature sensor and a dual range carbon monoxide (CO) sensor, providing an ability to detect fires and then subsequently monitor fire situations throughout the tunnel or structure. The use of a high fire withstand, ceramic clad wire is proposed for the charging line, which could in principle also provide tactile cues. The overall strategy has been to reduce beacon cost and installation complexity so as to allow beacons to be relatively closely spaced, and to provide a near continuous sequence of guidance cues, even where tunnel refuges or intermediate exits are relatively widely spaced. The system could also in principle provide an excellent platform to incorporate acoustic instruction and guidance information. With further commercial development, this proof-of-concept system is considered to have application potential across the generality of Europe’s road, railway and metro tunnels.

8. TUNNEL OPERATOR

A. van Waterschoot
Rijkswaterstaat, the Netherlands

J. Rypkema
TNO Human Factors, the Netherlands

J. leCoze
INERIS, France

8.1 Introduction

As was already mentioned in the chapters about evacuation, there is an important job for the tunnel operator in decreasing the time being lost in an incident. The operator needs to be stand-by in order to detect any incidents happening, to decide what is the most proper action to be taken and he needs to provide other people with information (road users, emergency services, other operators etc.). As was already identified in the earlier studies, information is very important in helping people make the right decisions. Since the role of the operator is such an important one (overview of the situation, possibilities to communicate to several services etc), this role will be the subject of this chapter.

The information from the tunnel operator is mainly derived from UPTUN Task 3.3 (the studies concentrating on the road user were part of Task 3.2). The objectives of Task 3.3 were:
a) To analyse the task of the operator, including the interactions with tunnel users and rescue teams; and then
b) To collect and / or generate means of support for the operator, based on this analysis.

The main participants who delivered input for this task were RWS (NL, task leader), TNO (NL), Maribor (SL), Ineris (FR), CERTH-HIT (GR) and COWI (DK).

8.1.1 Method

This chapter deals with tasks and behaviour of the tunnel operator and, more specifically, with possible methods for improving the operator's performance during incidents. These methods should be focused on bottlenecks that threaten adequate tunnel operator performance.

The first step towards improving operator performance is to list the operator's tasks during normal operation and incidents. Therefore, first of all, operator tasks as listed for a number of existing tunnels in Europe are described. Then bottlenecks are systematically identified, based on operator tasks, actual incidents in the past and operator's experience. The results are used to propose possibilities for improvement in operator performance. Five general methods to influence operator behaviour are translated into specific ways to improve operator performance. At the end, a strategy is proposed using the techniques from this report.

8.1.2 Sources

The analysis of operator tasks and bottlenecks is in part based on information from UPTUN deliverable 3.2, from several reports by the University of Maribor on tunnel operation in Slovenia, from Dutch data including a current safety review of tunnels in the Netherlands and from TNO reports on operator behaviour. Ineris produced a report on best practices for ensuring optimal emergency responses and on the requirements of a disaster management system. Also, several operators were interviewed using the questionnaire in Appendix 5 or a similar questionnaire. The questionnaire was also used as a tool to analyse abovementioned reports and literature sources.

8.1.3 Definitions

Bottleneck	Anything that hinders a tunnel operator in performing his tasks in preventing and handling incidents. → 8.3
Incident	Any disturbance of the normal traffic situation, from traffic jam or an animal on the road up to large fires and explosions.
Cognitive task load model	A model for cognitive task load, used to describe the tasks and the mental load of operators in process control environments. This model was used in this task to identify problems that can occur within the work of tunnel operators and define solutions for these problems. → 8.2, 8.3, Appendix 5
Situation assessment; Decision making and control	Task type sets based on the cognitive task load model. Situation assessment includes situation awareness and disturbance assessment tasks. Decision making and control includes decision making tasks and direction & control tasks. → 8.2

8.2 Operator tasks

Tunnel operator tasks vary from country to country. Tasks may include:

- securing safety for users both in normal conditions (prevention) and in the event of an incident;
- monitoring the efficient performance of all technical installations during normal operation and adjusting them as required during incidents;
- properly maintaining structural and electromechanical installations.

In this report, only the tasks of operators directly relevant for prevention and incident management are mentioned.

Two approaches are combined to analyse the operator tasks: generic task types and scenario analysis.
In 8.2.1, four generic task types for operators are mentioned. These task types relate mainly to the cognitive level at which tasks are performed.
Since the UPTUN project is aimed at the reduction of probability and consequences of incidents, operator tasks during the course of an incident are reviewed in this chapter, using a general scenario approach (8.2.1).

Sources from different European partners reveal a wide range of operator tasks in incident management on a more detailed level. In paragraph 8.2.2, an attempt is made to summarize these tasks, using both approaches described in 8.2.1.

8.2.1 Models used

<u>Cognitive task load model</u>

The cognitive task load model (Papaioannou & Georgiou, 2003; Rypkema et al, 2002) is a model, used to describe the tasks and the mental load of operators in process control environments. In this model, tasks are categorized in four generic task types:

1. Situation awareness
Continuous monitoring of traffic and critical parameters that represent the state of the tunnel. This means not only monitoring the state of the tunnel, but also the state of the installed equipment to detect any technical failures. The operator needs the right information to get insight in the actual situation and the

situation as it will be in the near future.

2. Disturbance assessment
The situation awareness information is used to assess incidents in the tunnel. In some cases, disturbances are directly solved by standard or rule-based procedures.

3. Decision making
When no standard procedure is available, the operator (together with others) might have to make decisions to prevent escalation of incidents.

4. Direction and control
Intervention in the tunnel and participation in rescue operations if necessary. The operator is crucial in incidents, especially in the first stages, prior to the arrival of rescue services.

In practice, the distinction between situation awareness and disturbance assessment may be difficult to make. The same goes for decision making and direction and control. Therefore, the four task types are clustered into two sets:

Situation assessment:	Decision making and control:
1. Situation awareness 2. Disturbance assessment	3. Decision making 4. Direction and control
Especially relevant in normal tunnel operations.	Especially relevant in incident situations.

<u>Incident scenario</u>

In different stages of the incident process, different strategies can be used to return to the normal operation of the tunnel. There are several ways to define the stages of an incident scenario. For the purpose of reviewing operator tasks, incident stages derived from the incident scenario in Table 7-1 are used. Note that these stages may (partially) overlap.

Table 8-1: Generic incident scenario

Incident stage	Includes
Prevention	Activities to reduce possible incident causes: prevention, pro-action. Preparation for effect reduction (such as education or developing procedures).
Incident	When a disturbance occurs, detection equipment sends a signal to the control room. The operator handles the disturbance in order to avoid escalation.
Most scenarios end here. Usually, the operator handles the disturbance in time to avoid escalation of the incident.	
Escalation	If the incident does escalate, the operator takes action to minimize undesired consequences, and prevent further escalation: he closes the tunnel for oncoming traffic; he switches the tunnel equipment to the emergency operation status.
Alert	The operator alerts: rescue services; other operators, where applicable; tunnel users, instructs them to escape if necessary.

Incident stage	Includes
Self rescue	Tunnel users leave the car; may try to help others evacuate; may try to correct the situation; flee to safe place.
Rescue by rescue services	All activities performed by fire rescue, medical rescue, police and towing service, to limit consequences to tunnel users and tunnel, and to prevent further escalation. The operator assists the rescue services. Rescue of remaining tunnel users; putting out fire; removing vehicles and obstacles (towing service); switching tunnel equipment to normal status (and check); re-opening tunnel by proper authority.
Follow-up	After situation has been returned to normal: evaluation and aftercare.

8.2.2 Operator tasks

In Table 8-2, the operator tasks are listed following the generic incident scenario. The tasks are categorized into the two task type sets as described before.

Table 8-2: Operator tasks

Incident stage	Situation assessment task	Decision making and control task
Prevention	Monitoring the traffic flow and situation in the tunnel (and vicinity) using cameras, sensor readings and communication equipment. Note: constant vigilance is required.	
	Monitoring the installed equipment.	Making a decision about urgency when tunnel equipment fails: repair now or later? To call maintenance staff to repair the failure.
		Preparation for effect reduction: education, training, exercises.
Incident	Fast and correct detection of incidents.	Handling disturbances in order to return to the normal situation and avoid escalation: for example, flat tyre: close lane, help driver (phone), return to normal.
Escalation	Keeping alert, monitoring for additional disturbances or possible further escalation.	Closing the tunnel; switching equipment to 'emergency mode' (lights, ventilation, speed limits, escape doors, et cetera).
Alert		Alerting other operators (where applicable), rescue services and tunnel users (instructing them for escape if necessary).
		Alerting other authorities.
		Taking traffic measures to clear the road for

Incident stage	Situation assessment task	Decision making and control task
		the rescue services.
Self rescue		Communicating with tunnel users to help them escape and to help them help others or correct the situation (for example: putting out a small fire).
Rescue by rescue services	Being the 'eyes and ears' inside the tunnel for the rescue services.	From the control room, assisting the rescue services in their rescue operation.
		Implementing detours for oncoming traffic if necessary.
		Arranging to remove vehicles and obstacles. Arrange to restore tunnel and tunnel equipment to normal, and check.
		Re-opening the tunnel after authorization.
Follow-up		Evaluating and registering the incident for the purpose of improvement.

From this table it is apparent that, the moment an incident occurs, many time-critical "Decision making and control" tasks have to be executed in the incident process. This phenomenon will be explored further.

8.3 Bottlenecks

In theory, the tasks listed in 8.2 are sufficient to minimize injuries and damages and quickly return to ‘business as usual’. But: in reality, things can go wrong due to several causes.

Two approaches were used to identify bottlenecks:
1) Starting from the operator’s tasks, factors can be identified that influence the probability of the operator making errors (cognitive task load model, see below).
2) Incident reports identify several (possible) bottlenecks that, directly or indirectly, negatively influenced the situation.

8.3.1 Models used

<u>Cognitive task load model</u>

The cognitive load model (Papaioannou & Georgiou, 2003; Rypkema et al, 2002) distinguishes three load factors that have a substantial effect on task performance and mental effort:

1. Percentage time occupied: the percentage of available time that the operator is occupied with his or her tasks. The higher this percentage is, the higher the cognitive load.

2. Level of information processing: relates to the complexity of tasks. This factor is based on the Skill-Rule-Knowledge framework of Rasmussen (1986), in which skill-based tasks demand the least cognitive effort and knowledge-based tasks the most.

3. Number of task-set switches: refers to the number of switches the operator has to make between different task-sets. The more switches, the higher the cognitive load.

Combination of these factors yields an indication of the operator's cognitive load, see Figure 8.1.

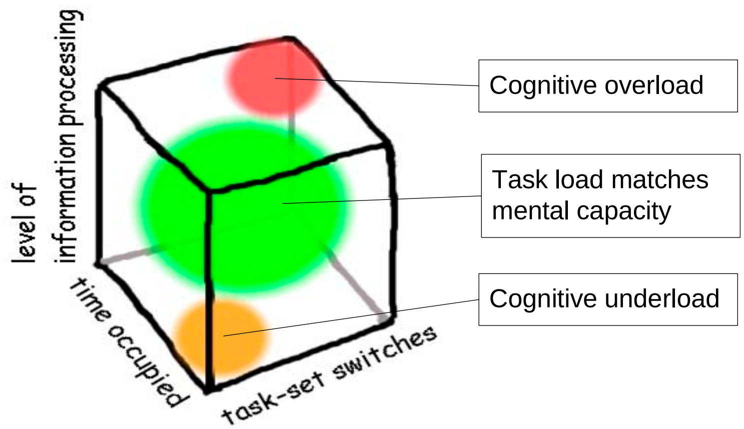


Figure 8.1: Schematic representation of the task load model

Cognitive *overload* (red area) can occur when one or a combination of the following situations is present:
1) The operator does not have enough time to finish the tasks.
2) The operator tasks are too complicated.
3) The operator has to perform too many tasks at the same time.

On the other hand, if all three factors can be characterized as "low", cognitive *underload* can occur (orange area). Cognitive underload, just as overload, may lead to sub-optimal performance. For example, it may have a negative effect on vigilance.
Ideally, all three factors are in between these two: in that case the task load matches the operator's mental capacity in a certain task setting (green area).

<u>Error types</u>

(Possible) bottlenecks may cause different types of errors. Figure 8.2 is a schematic representation of a model described in Papaioannou and Georgiou (2003).

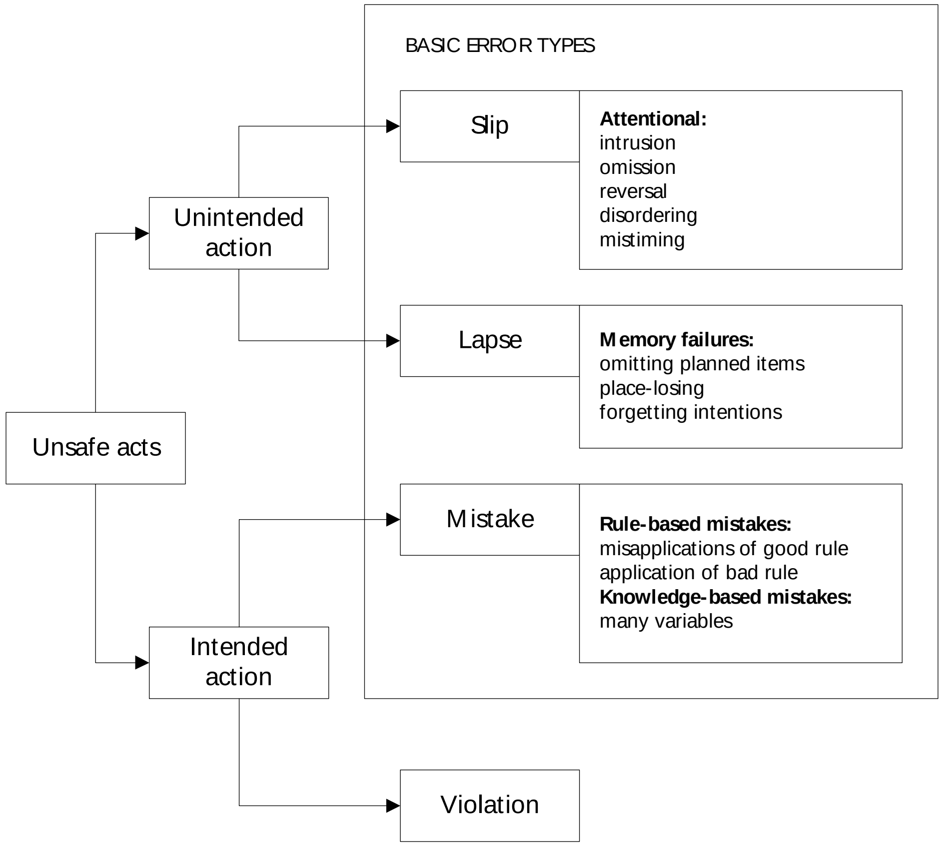


Figure 8.2: Error types

In 8.3.2, an attempt is made to identify error types connected with each of the bottlenecks. This is done to help direct the search for possible solutions. For example, for ‘application of bad rule’ (rule-based mistake), the solution most likely to be succesful is ‘change the rule’.

8.3.2 Bottlenecks

Table 8-3 is a list of bottlenecks from the sources mentioned in the previous paragraph. Table 8-2 was used to link operator tasks and bottlenecks.

It should be noted that a number of bottlenecks may occur in various incident stages. This is mainly due to the fact that lack of adequate preparation causes bottlenecks during an actual incident. In the table, bottlenecks with consequences throughout the incident process are listed under the heading 'Prevention'.

Previously it was already mentioned that many tasks during the incident handling process can be categorized as ‘Decision making and Control’ tasks. Also, these actions have to be completed in as short a time as possible. This may cause cognitive overload as described in the Cognitive Task Load model (see Bottleneck #7 in the table).

This phenomenon is partly related to the fact that in many cases, there is a lack of adequate incident handling procedures, insufficient coordination and communication with rescue services as well as a lack of exercises.

Table 8-3: Operator tasks (from Table 8-2) and bottlenecks[7]

Incident stage	Situation assessment task	Decision making and control task	#	Bottleneck	Bottleneck type
Prevention	Monitoring the traffic flow and situation in the tunnel (and vicinity) using cameras, sensor readings and communication equipment. Note: constant vigilance is required.		01	During long periods of normal operation, vigilance may be threatened. This is especially critical during the night (3-6 a.m.), when tunnel users are also less alert.	Cognitive underload risk
		Preparation for effect reduction: education, training, exercises.	02	Bad or absent incident handling procedures; especially unclear allocation of responsibilities and authority to personnel.	Rule-based mistake: no rule or bad rule
			03	Insufficient skills due to lack of practice exercises, especially with the rescue services.	Knowledge-based mistake
Incident	Fast and correct detection of any event or disturbance likely to escalate into an incident.		04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.	Suboptimal cognitive load
			05	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in	No error but lack of tools or wrong tools

[7] Some bottlenecks are listed twice in the table. Under "Bottleneck type", bottlenecks are categorized according to the cognitive task load model and the error type model. Some bottlenecks may fit into one of two categories, depending on the actual cause in a specific case. In this table, these bottlenecks are listed with both relevant categories. In the next chapter, both categories will be necessary when a link-up of bottleneck types and generic solutions is used to help the search for solutions.

Incident stage	Situation assessment task	Decision making and control task	#	Bottleneck	Bottleneck type
				tunnel.	
			06	Operator is panic-stricken and does not respond (adequately) to incident.	Unintended action
Escalation		Closing the tunnel; switching equipment to 'emergency mode' (lights, ventilation, speed limits, escape doors, et cetera).	07	Starting from the escalation stage, many different decisions and actions are required in a short time.	Cognitive overload risk
			08	Too many incoming signals, not all of which are relevant at this time.	Cognitive overload risk
Alert		Alerting other operators (where applicable), rescue services and tunnel users (instructing them for escape if necessary).	09	Insufficient means to communicate with other operators, rescue services or tunnel users.	No error but lack of tools or wrong tools
			10	Insufficient skills and / or knowledge to communicate with other operators, rescue services or tunnel users.	Knowledge-based mistake
Self rescue		Communicating with tunnel users to help them escape and to help them help others or correct the situation (for example: putting out a small fire).	11	Operator does not succeed in convincing tunnel users to escape.	Rule-based mistake: misapplication
			12	Operator does not indicate right way for fleeing or does this too late.	Knowledge-based mistake
Rescue by rescue services		From the control room, assisting the rescue services in their rescue operation.	13	Absence of or insufficient coordinated procedures between operators and rescue services.	Rule-based mistake: no rule or bad rule

Incident stage	Situation assessment task	Decision making and control task	#	Bottleneck	Bottleneck type
Follow-up		Evaluating and registering the incident for the purpose of improvement.	14	Absence of adequate incident evaluating and registration procedures.	Rule-based mistake: no rule or bad rule
			15	Mistake in incident is not evaluated or registered due to fear for career consequences.	Violation
			16	Incident is not evaluated or registered although adequate procedure is available and known.	Violation

8.4 Possible solutions

Improving operator performance can be achieved through a number of improvement methods:

1) Recruitment
2) Training and exercise
3) Personnel and organisation
4) Task support (such as procedures and guidelines)
5) Control room and interface design

Paragraph 8.4.1 discusses possibilities to prevent cognitive underload or overload by applying the improvement methods mentioned above. Paragraph 8.4.2 lists recommendations for each of the improvement methods, based on the bottlenecks identified in paragraph 8.3.

One of the tables in Appendix 7 contains the bottlenecks identified in paragraph 8.3, along with possible solutions. No attempt has been made to list *all* possible solutions, but for each bottleneck, some solutions are mentioned. Appendix 8 provides some background information on available tools and techniques mentioned in this report and supporting the solutions.

8.4.1 Optimizing cognitive task load

<u>Solutions for cognitive underload</u>

The earlier and the more correctly a disturbance or an incident is detected, the bigger the chance that it is handled quickly and adequately. This requires constant vigilance on the operator's part. Cognitive underload is a serious threat to the operator's vigilance.

Solutions for cognitive underload

a) Limit operator's duties to a few hours at a time.
A practical solution is to have (at least) two staff members on duty, both qualified to perform operator's tasks, switching roles every few hours. One of the two may be performing other activities, while the other one is monitoring the tunnel.

b) Force the operator to employ activities from time to time.
Some tunnel owners choose an operating system that generates alarms if nothing has happened in the last, say, ten minutes. When this happens, the operator is required to take certain actions in order to disable the alarm, for example check on some part of the tunnel equipment.

Of course, a prerequirement for solution "a" is the availability of enough operators. If there can only be one operator on duty, activities besides actual operator tasks may not be possible.

Solutions for cognitive overload

The five improvement methods can all be used to lower cognitive task load. To be able to choose the most effective combination of measures, it is necessary to know the causes of cognitive overload (see also 8.3.1):

1) The operator does not have enough time to finish the tasks. The solution might be to reduce the number of tasks or the time required for individual tasks.

2) The operator tasks are too complicated (level of information processing: skill < rule < knowledge). Improvement by reducing the level of information processing.

3) The operator has to perform too many different tasks at the same time, including the interpretation of incoming signals irrelevant to the incident. Improvement by reducing the number of tasks and incoming signals.

Also, it is necessary to establish at what point in the incident process cognitive overload is likely to occur. Common times in the incident process where overload may be a threat are:

1) Detection: if the operator is too busy performing other tasks than monitoring, he may not notice an incident in the tunnel. The more other tasks and the more complex these other tasks, the greater the chance of this occurring;
2) After detection of a (serious) incident, many additional signals come in while at the same time the operator has to perform many different tasks in a short time;
3) Decision to evacuate: based on the assessment of the situation in the tunnel, the operator has to make the difficult decision whether or not evacuation is necessary. In a fire, lives may depend on this decision and especially on its timing.

Solutions for cognitive overload

c) Reduce the time required for a task and the number of different tasks required.

The operator's work station (hardware and software) should be designed in such a way, that all controls, switches, phones et cetera can be reached in an instant. Also, the number of actions that the operator needs to take during an incident should be limited to a minimum.

d) Reduce the level of information processing required for a task by providing adequate procedures for incident management and regular training and exercise based on these procedures. This way, tasks will move from knowledge-based to rule-based to skill-based.

e) During an incident, reduce the number of incoming signals to only those important for handling the incident.

Figure 8.3 shows a (very) crude representation of an analysis of cognitive overload threat. Both the incident scenario and the cognitive task load parameters were used to gain an insight into the overload danger. Scenario analysis (See Appendix 8) can assist in specifying the tasks and actions required and the time needed to complete them.

When choosing improvement methods, attention should especially be given to tasks occurring in those stages, where cognitive overload is most likely to occur. In the example presented in Figure 8.3, this would be the incident, escalation, alert and self rescue stages.

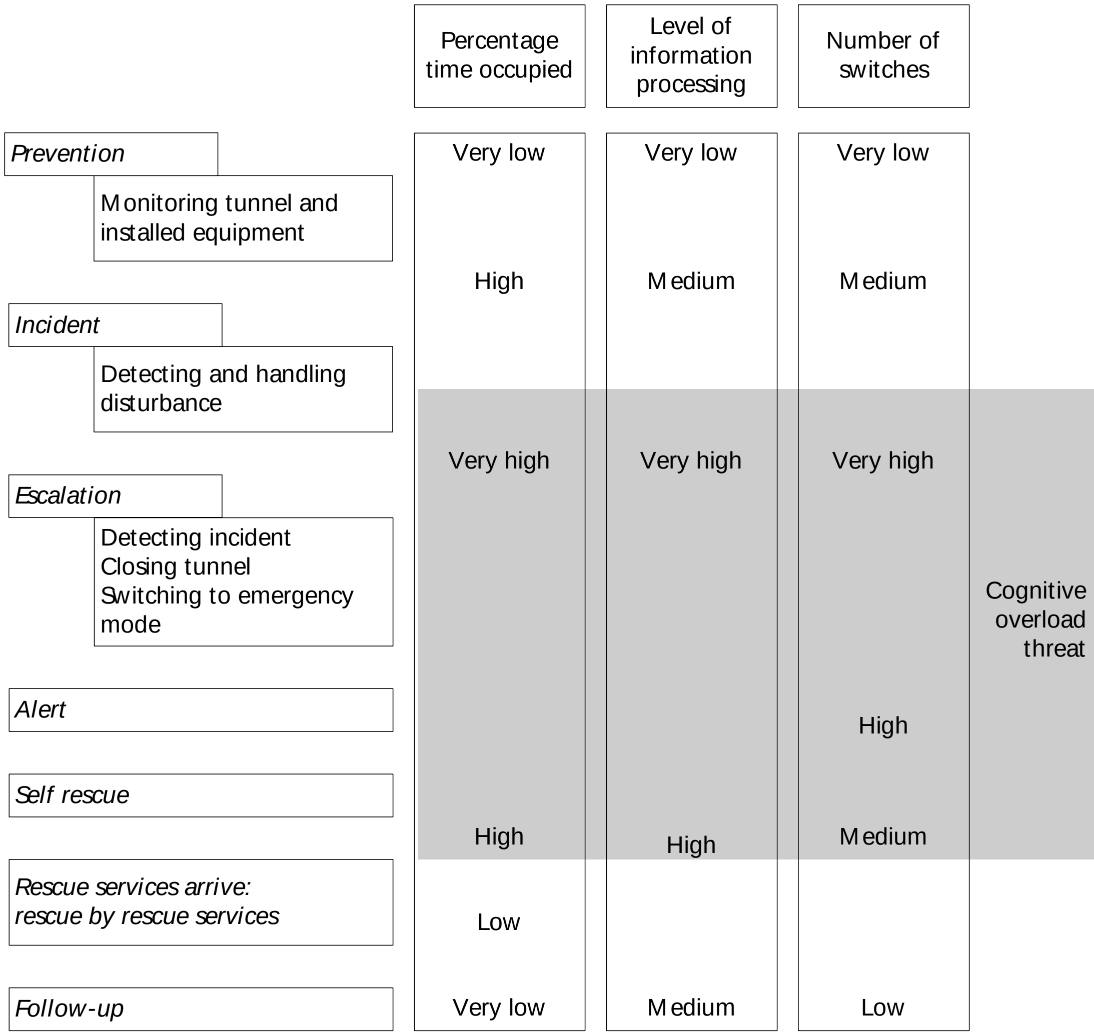


Figure 8.3: Example of an analysis of cognitive overload threat

8.4.2 Possible solutions to bottlenecks

Depending on the type(s) of error connected with a bottleneck, a generic match for bottleneck types and solutions was used to assist the search for possible solutions.
For example, education is often the answer to knowledge-based mistakes, and if, for a certain task, tools are unavailable or inadequate, the obvious solution is to change them or provide the right tools. This provides an indication for the improvement methods likely to be effective.
Appendix 7 contains one table which lists the bottlenecks from beginning to end of the incident scenario. Another table lists the same bottlenecks, rearranged into the five improvement methods. These tables were used to write the recommendations in this paragraph.

<u>Recruitment</u>

Certain personal characteristics are of the utmost importance when recruiting personnel for tunnel control centres, more important than knowledge or technical skills.

In a PIARC (AIPCR) working group, a 'Good practice' for the operation and maintenance of road tunnels was produced (PIARC, 2004). Part of this is an extensive set of recommendations for recruitment, training and exercises for tunnel operating staff. The PIARC report mentions prerequisites for recruitment and requirements for personal qualities and training levels for traffic control and incident response staff.

This report, therefore, merely suggest some specific staff selection criteria, based on the identified bottlenecks.

> Solutions: recruitment
>
> Apply staff selection criteria:
>
> 1) candidate should be able to handle stress, especially during incidents when tunnel users may be in danger;
>
> 2) candidate should possess excellent communication skills; should be able to communicate with tunnel users in such a way, that:
> - tunnel users are aware of his authority;
> - tunnel users are immediately aware of the urgency of the situation and, where applicable, the need to escape;
> - he does not convey any feelings of panic onto the tunnel users;
>
> 3) candidate should be able to evaluate his own work, in order to effectively evaluate incidents; should be able to make improvements based on this evaluation (attitude / self-learning).

<u>Training and exercise</u>

Education provides a basis for the required skills and knowledge for managing an incident. Due to the fact that large-scale incidents – luckily – do not happen very often, experience cannot be relied upon to reach and keep the desired level of knowledge and skills. Additionally, the operator needs to know the existing procedures and specific characteristics of the tunnel he is monitoring.
Therefore, it is essential to keep the operator's knowledge and skills up-to-date in other ways, for example by regular training and exercises.
Exercises with the emergency services, in addition, will influence the quality of communication between the operator and emergency services.

Also, the PIARC document (2004) provides a large number of recommendations for basic training, ongoing training and exercises (with or without emergency services).

Training and exercise (no matter what the subject is) can be used to increase cognitive load: keeping the operator alert by performing exercises at certain times. On the other hand, training and exercise can also be used to lower cognitive load by lowering the level of information processing. See also paragraph 8.4.1. In Appendix 8, some training techniques are discussed.

Solutions: training and exercise

4) Include incident management procedures in both basic and ongoing training. Not only to enhance the skills of the operators and others involved, but also to evaluate the procedures themselves.

5) Include tunnel lay-out, location and operation of all safety measures, including communication devices in basic training.

6) Train communication skills.

7) In addition to the actual training and exercise programme, require operators to take periodical tests to make sure the training programme is carried out as it should be.

Personnel and organisation

The number of people or allocation of tasks should be optimally suited to the number and nature of control room tasks. However, if these personnel matters would only be based upon an efficient distribution of tasks, the result could be that only one operator on duty should suffice. In that case the tunnel owner should use caution: practical complications may occur. In this case it may be recommendable to search for alternatives such as having two operators present at all times (see also 7.4.1).

The effect of characteristics of the tunnel management organisation should not be underestimated when analyzing operator performance.
For example, every tunnel management organisation should have an excellent communication network with the emergency services to ensure that the duties of rescuers and tunnel operators are smoothly coordinated.
Another example: in some organisations, mistakes or errors are not evaluated or registered due to fear of punishment (adverse effects on career). As a consequence, the organisation misses out on the opportunity to learn from mistakes made by its employees.

Solutions: personnel and organisation

8) Make sure there are enough operators on duty (and spares) to switch roles from time to time and to assist during incidents.

9) Stimulate communication on a regular basis with the emergency services to coordinate and facilitate incident handling procedures.

10) Make sure the company culture provides an environment that supports the company goals (including the learning process).

Task support

During an accident or calamity, the operator must – as much as possible – be protected from making mistakes and from making the wrong decisions under great stress (due to cognitive overload, see 8.4.1). The number of decisions to be made by the operator must therefore be limited to a minimum. This can be achieved by standardization, which includes both procedures (exactly how to act in an incident) and tunnel safety equipment.

Procedures and plans may deal with:

- Preventive measures (e.g. maintenance schedules for technical installations)
- Adequate management of disturbances.
- Adequate incident management:
    - Communication: who gives what information how and to whom?
    - Who is authorized to do what at which moment?
    - Appendix 8 contains some more information on calamity plans..
- Incident evaluation and registration aimed at improvement by learning from mistakes.

Some kind of manual or procedure book is usually the carrier of this information. The existence of such a manual is, of course, not enough: the manual and its contents have to be available and known to all parties. Moreover, a manual has to be easily understandable to the persons who have to use them. Tools such as summarizing flow charts and reference cards may help.

Also, using procedures only *starts* by writing them. In order to successfully use procedures as part of a solution, attention should be given to instruction and implementation as well.

Solutions: task support

11) Decide for which tasks procedures are useful.

12) Write the procedures using knowledge and experience of all relevant parties.

13) Make sure everyone who plays a role in a procedure has access to it.

14) Make sure that time-critical procedures are well-known and can be found fast (for example: short instruction card on operator's desk).

15) Exercise the procedures on a regular basis.

Control room and interface design

The operator's work place should provide an adequate environment for him to keep alert and perform his tasks efficiently. Control room and interface design provide opportunities to support an optimal cognitive task load.

An interface should provide complete and correct information on the situation in the tunnel as quickly and easily accessible as possible.

During normal operation, incoming signals warn the operator about low traffic speed in the tunnel or equipment malfunctions. Depending on the situation, the tunnel operator may decide to act on those incoming signals one way or the other. When, however, an incident is in progress, several alarms will sound and keep going, distracting the operator from more important tasks such as guiding tunnel users towards a safe exit.

Ideally, during an incident, the operator should only hear or see alarms that directly influence the safety in the tunnel at that time. For example, a low traffic speed alarm is no longer relevant if the operator already knows that there has been an accident and the tunnel is blocked. On the other hand, if at some point fire detection gives a signal, he should immediately instruct the tunnel users to escape.

Tools are available to limit the time needed for certain tasks and limit incoming signals (as illustrated in Figure 8.4). Control room and interface design may also assist in keeping the cognitive task load above a minimum level (see also 8.4.1). For example, temperature in the control room can influence alertness. Another example: generating a sound signal if the system has registered no activity during a specified period of time.

Using technology to improve operator performance only works if it supports other measures, and if its operation is trained on a regular basis.

Figure 8.4: Standardizing operator tasks

Solutions: control room and interface design

Possible tools:

16) Tools for cognitive support (Appendix 8). Such tools, if based upon correct procedures, can assist the operator.

17) A command group (Appendix 8): two or more actions are triggered by one button, limiting the number of actions required to complete a task. For example: the so-called 'calamity button' in the Westerschelde tunnel (The Netherlands) (Appendix 8). As soon as a serious incident is detected, the operator pushes the button, and the lighting level goes to maximum, ventilation kicks in, escape route systems are activated, and so on.

18) Tools facilitating the evacuation process (Appendix 8). Communication with tunnel users to guide their escape is a time-consuming and high-pressure task for the operator during the incident.

19) A switch for the operator to disable all irrelevant alarms during an incident. If a calamity button is applied, the underlying commands may include such a suppression mode. An additional solution is creating the possibility for the operator to stop a specific signal, as soon as he is aware of the problem.

20) A combination of loud alarms and visual signals if a crucial factor, for example fire, has been detected to make sure that, even if the operator is less alert than usual, the disturbance is noticed.

8.5 A strategy

A tunnel owner can follow these steps to improve operator performance.

Step 1: Make an inventory of the operator's tasks.
In this report, mainly tasks related to incident management are mentioned. However, in many cases, the operator has additional tasks, such as maintenance tasks, traffic control tasks or manning toll booths. These extra tasks should also be taken into account, and may even provide possible solutions to some bottlenecks. For example, cognitive underload may be prevented by having two or more tunnel operators switching roles from time to time, and performing monitoring tasks for only a limited number of hours at a time.
The first step is to make an inventory of all the operator's tasks. This could be done using the cognitive load model and scenario analysis (see 8.2).

Step 2: Identify bottlenecks, using the task list, knowledge and experience.
The task inventory could already reveal threats, such as possible task overload at certain times during an incident. Using the cognitive task load model and the combined European experiences with minor and major incidents, possible bottlenecks can be identified the way this was done in 8.3.
Also, tunnel owners and operators usually have sufficient knowledge and experience in handling (minor) incidents to identify additional bottlenecks specifically applicable for the local situation and the tunnel owner's organisation.

Step 3: Interview to check, complete and prioritize the bottleneck list.
The lists of tasks and bottlenecks may be used as a basis for interviews with tunnel operators and other relevant parties (such as emergency services). They may provide new suggestions from a different point of view.
Appendix 5 is a questionnaire that may be useful for interviewing operators. Operators and rescuers may also help prioritize the bottlenecks.

Step 4: Find solutions for the most important bottlenecks and design an improvement strategy.
Using the prioritized list of bottlenecks and the general methods for influencing operator behaviour mentioned in 8.4, generate possible solutions for the most important bottlenecks.

For different tunnels, different solutions or combinations of solutions may prove to be the most efficient. Sometimes, two birds can be killed with one stone. For example, an exercise in cooperation with the emergency services may (1) improve the operator's skills, (2) improve communication between the tunnel management organisation and the emergency services, and (3) reveal irregularities in incident procedures.

On the other hand, in most cases, there is more than one effective solution to a problem and some improvement methods even inherently require combination with another one in order to be effective. For example, it serves no purpose to provide software to log and evaluate incidents, if the organisation culture punishes those, who admit to making mistakes.

Which way to choose, then? An effective strategy to reduce the most important bottlenecks relevant to a tunnel (or set of tunnels) should be a balanced mix, depending on, amongst others, the following factors:

- which, and how many, bottlenecks are relevant to the situation;
- local circumstances (for example: if the tunnel lies in two language regions, control centre personnel could be selected from both);
- presence of other problems that need to be solved;
- characteristics of the tunnel owner's organisation.

Your strategy for improving operator performance is now complete.

Step 5: Plan and execute your strategy.
Based on the strategy, a plan can be written to implement the chosen solutions. This plan should include assessment: when and how to check if the solutions were effective in attaining the goals of the strategy.
Depending on the factors mentioned in the former step and the means available to the tunnel owner, a large number of tools and techniques supporting the solutions is available. Appendix 8 may be helpful at this point.
When the plan is ready and approved by the proper authorities, it is executed.

Step 6: Assess the effect.
Based on the plan, at several times during the implementation process and at the end, the effectiveness of the chosen strategy is assessed.
Progress can be measured by comparing the original lists of tasks and bottlenecks to the present situation. Interviewing operators again, using the questionnaire (Appendix 5), may be helpful in finding the answer to the question: "Do the solutions really work?"

Revision of the strategy may be necessary if the outcome is not as desired.

9. OVERALL CONCLUSIONS

This report focuses on road user and operator behaviour in tunnel incidents. Several studies have been conducted in order to update the knowledge about the behaviour in order to improve proper actions in case something really happens.

In order to understand what is going on in tunnel accidents the *accident happening model* was presented, being a combination of the model of triadic reciprocal causality, the task capability model, the model of driver and recognition-primed decision model. This model provides some key processes that contribute to the safety of tunnel use. The model focusses on the user behaviour in tunnel

Safety considerations in relation to the respective parts of the model are the technical characteristics of the tunnel design and infrastructure (should always take the planned role of tunnel users (drivers, operators, and maintenance and emergency personnel) into account when talking about design), rules of the safe use of the tunnel (the tunnel rules and their violation must be clear to the users and operators), diagnosis of the tunnel situation, behavioural decision making process, user's behaviour in traffic, behavioural consequences (e.g. accidents).

The proposed accident happening model integrates the elements of other models in a way that supports the process of designing the road tunnels. The following elements are specifically emphasised:

- The process of designing the tunnel implies the physical, normative and social environment of the tunnel users. In this process existing information about user's behaviour is deployed. The additional necessary information must be obtained with relevant research.
- The process of designing the tunnel is interdisciplinary. The exchange of ideas between different disciplines must be planned.
- The proposed model emphasizes the importance of normative environment (rules for utilization of the tunnel). The rules complement the physical design and are important regulators of the user's behaviour.
- The proposed model emphasizes the fact that the events in the tunnel take place in a social context (other participants). The consequence of this fact is that we must consider the tunnel as a socio-technical system and take into account the processes of so called "*social construction of safety*" (Rochlin, 1999).
- It follows from our model that the process of user's interpretation of the tunnel situation is a major determinant of the safe behaviour. For the understanding if this interpretation, the safety culture of the user must be taken into account. This topic requires more research.
- The model incorporates the difference between automatic and conscious human information processing. Much information relating to safety culture is processed automatically.
- This model emphasises the systemic and circular regulation of the safety in tunnel. One regulatory loop occurs on the behavioural level of the user. The consequences of the user behaviour are feed-back to his interpretation of tunnel situation. The second loop occurs on the system level. The consequences of user behaviour are feed-back to the tunnel designers and operators who make necessary reconstructions and interventions to improve the safety.

With this model in mind, it is important to see how this decision making process of road users actually develops, when do people respond and based on what type information. In order to look at the drivers' responses, two driving simulator studies were performed, one with passenger car drivers and one with truck drivers. From these studies we can learn:

- We can conclude there is indeed difference in response and understanding the urgency of the situation if people have more information. Although some people understand what is going on and what they have to do spontaneously, having read extra information about how to behave improves the situation somewhat, but best results are found if (besides reading the EU leaflet), the operator also states what people need to do.

- Even if a tunnel operator tells them what to do, there is not a 100% correct behaviour.
- Not too many people use the radio to get additional information, not even after reading the leaflet (which instructed people to do so). Even if people used the radio, they did not remember the frequency presented in the leaflet. So in case there would be a radio message, it should be broadcasted via all radio channels.
- Some people specifically mentioned that they planned to walk back to the entrance of the tunnel instead of using the emergency doors, which they were required to do, especially people without any additional information. Even though people already had driven the tunnel several times before the incident (so they could have seen the emergency doors), some people still want to use the tunnel entry as an exit.
- Quite some people indicated that they did not have an idea of how to handle in the given situation (even in the condition with leaflet and operator). This means that there is a lot of uncertainty in the case of accidents or incidents in tunnels, and even though there is an operator voice, even though people read the leaflet, there is still uncertainty how to behave. Even though designers may think that all information needed is there, this may not be enough for the road users. Information provided needs to be over-complete, with if possible a repetition of the messages. Also, people with visible official status should be sent inside the tunnel in order to help people make the right decisions. Also, as was also discussed in the PIARC committee, we need to have people with an exemplary behavioural function, for instance professional drivers.
- Some people indicate not to have handled because of the smoke. Although this should actually indicate the severity of the situation, this leads them not to respond. Even after reading the leaflet (indicating smoke and fire can kill), some persons mentioned that they were waiting for a signal or information on the radio to leave the car. Even if the operator informed road users, one person mentioned that it was unclear where to go and one person indicated to need more clarity of how to respond.
- One of the good results of reading the leaflet may be that no-one after reading the leaflet mentioned that they did not take any action because they waited for others to take action (3 people indicated this without reading the leaflet).
- One person (without reading the leaflet) mentioned he felt safer in the car and one person (even after hearing the operator) simply mentioned that he wanted to get out but was afraid to do so. The fact that a lot of people mentioned the smoke as the reason to take action, we have to be careful with getting the smoke completely out of the tunnel: this may enhance the delay in response time.
- However, that reading the leaflet is not enough is shown by the people who said that they did not take any action (e.g. because they did not want to panic, did not see any panic, tried to stay calm, were looking for more information etc) even though they read the leaflet. In the case there was also operator instruction, less people stated that is was not necessary to respond.
- Some people still miss warnings signs, information about what is going on, how serious it is and what to do, the need for information to be more extensive or information on the radio. As remarks on how to improve safety, some people indicated to place signs on what is going on and what needs to be done instead of only placing telephones and fire extinguishers, and put an alarm warning signal.

The train and car evacuation observations showed us that:

- Motorists need some sort of information from the operator.

- Group effect need to be modelled, since the modelling up to know treat the group as a number of individuals, each of them randomly assigned to one particular reaction type. An alternative way of modelling is to assign all motorists *as a group* to one, and only one, reaction type; for another follows where one sheep goes. Again reflecting the empirical observations, the odds that the whole lot is assigned to a "passive reaction" type is quite large. They will stay in the car until the call of the operator.

- The current data about train evacuation permit accurate estimation of the flow of passengers through the train exits, that could well be the bottleneck. It was revealed that the flow depended strongly on the vertical distance to the platform and, somewhat less, on the luggage carried. There are no data on awareness time and hesitation time.

- When evaluating the design of tunnels on evacuation safety it is important to compare the evacuation time required with the time available, for example the period when there is not yet a high density of toxic smoke and heat is not yet unbearable. When a tunnel is designed, such analyses should be made to see whether time available matches with evacuation time. evacuation safety is poor if there is no match, and measures are required.

- The current data underline the high efficiency of early and adequate public announcements; of more or wider emergency exits; and of escape ways without steps.

The sound beacons studies show that:

- Auditory guidance can be very effective (> 90%) under conditions of poor visibility, given that the sound used for guidance suits the expectations of the evacuees. Our self-explanatory sound beacons called " exit here" preceded by a dinner bell sound. Even without advance instruction, they offered help to test participants looking for refuge and a way out.

- All participants except one went to the nearest emergency exit with the self-explanatory sound. This was 55% in a previous test with a beacon sound that was not self-explanatory (Boer & Withington, 2004). The RW system will be effective only if evacuees are informed in advance about the sound and its meaning.

- In the tunnel, we observed a walking speed with the self-explanatory beacons above the one in the previous tunnel test with RW beacons (Boer and Withington, 2004). We ascribe this to more psychological confidence evoked by the self-explaining beacons of the current tunnel test, promoting walking speed for that reason. In a real disaster, motorists may have to walk a tunnel filled with untidily parked cars and, perhaps, debris.

- Sound beacons will also be useful under conditions of good visibility. The continuous repetition "exit here" will help motorists to understand that they should leave their car and find refuge. The beacons can thus help to overcome the initial passivity of motorists surprised by a disaster.

The innovative CRISP evacuation mode was elaborated for UPTUN. The salient features of CRISP were reviewed, in particular the decision-making process and the way it is influenced by smoke and people's assessment of the tenability level. This led to the development of the following behavioural rule sets:

- Train driver / train staff / rail tunnel staff
- Coach or bus driver / road tunnel staff
- Rescue / emergency services
- Rail tunnel public
- Road tunnel car drivers
- Road tunnel passengers
- Dependent members of the public (eg. disabled, young children, etc)
- Most of the actions and conditions had been developed in the context of building fires, and required different parameter values such as the allowed tenability level before abandonment, delay time distributions at completion, etc.
- Exit choice probability distributions have been simplified to a probability of heading to the nearest portal, or the nearest side exit (in both cases provided that a tenable route exists).
- Various options for people moving in groups were described. Groups may include families, people with some prior social affiliation, rescuer / dependent pairs, and other ad-hoc formations.
- The effect that luggage may have on people's behaviour and movement has been considered. One way in which this may be simulated is to regard large items as a class of dependent "people", needing to rescued, slowing the movement speed of the rescuer once the luggage is being carried, and obstructing the movement of other people.
- In rail tunnels, there may be a significant drop in height from the train to the track, walkway or platform. Currently in CRISP the flow rate of people through doors is limited by the effective width of the door, but it would be a simple matter to include the height difference as another factor in the time delay.

In order to help people evacuate after they have actually made the decision to evacuate, an innovative evacuation system prototype was developed, with the following properties:

- Use of fixed direction high intensity light emitting diodes, configured as a highly visible flashing arrow. This system is used where there is a fixed evacuation route and offers 1.5 hours operating life once activated.
- The units can be equipped with a sounder unit to aid localisation in heavy smoke conditions.
- An 'intelligent' programmable system has now been developed. In addition to contactless power transfer, this system incorporates telemetry to and from each of the beacon units. Each unit is addressable and can be remotely interrogated or controlled. The units can have their wayfinding direction reassigned individually or in blocks (for example to match tunnel ventilation sections).
- Further facilities include the ability to provide short-term power to internal or external sensors, the ability to undertake limited signal processing), and the telemetry of readings, status conditions and alarms back to the central controller.
- An alert button is also incorporated in the beacon design to permit occupants to call for assistance.

- Use of an intelligent beacon, incorporating an internal dual-range carbon monoxide sensor and a precision temperature sensor. This provides a distributed fire detection capability. This information also helps to determine whether rescue is feasible. The CO sensor incorporates a cell self-test function, where under software instruction, a small volume of gas is liberated within the electrochemical cell itself providing a direct test of cell operation.

- Whilst these applications are merely speculated, the underlying system concept is technically capable of operating in an above ground, tunnel or submerged application environment.

With respect to the tunnel operator, several theoretical models as well as information from experience were used to identify problems that can occur within the work of tunnel operators and to define solutions for these problems. Based on the results of the analysis, a strategy was proposed for improving tunnel operator performance, which can be summarized as follows:

Step 1 is used in order to identify the tasks. An inventory is made of all operator tasks, classified in situation assessment and decision making and control. This concerns tasks during normal situations (e.g. a traffic jam) and incidents or accidents (e.g. a fire).

Step 2 is used for an inventory of bottlenecks, which is the result of using the questionnaire. Using the cognitive task load model and the combined European experiences with minor and major incidents, possible bottlenecks can be identified the way this was done in 7.3.

Step 3 is used for interviews to check, complete and prioritize the bottleneck list.

Step 4 is used for finding solutions for the most important bottlenecks and designing an improvement strategy. Using the prioritized list of bottlenecks and the general methods for influencing operator behaviour generates possible solutions for the most important bottlenecks. An effective strategy to reduce the most important bottlenecks relevant to a tunnel (or set of tunnels) should be a balanced mix, depending on which, and how many, bottlenecks are relevant to the situation, local circumstances, presence of other problems that need to be solved and the characteristics of the tunnel owner's organisation.

Step 5 is used for actually planning and executing the chosen strategy. Based on the strategy, a plan can be written to implement the chosen solutions. This plan should include assessment: when and how to check if the solutions were effective in attaining the goals of the strategy.

Step 6 is used for assessing the effect. Based on the plan, at several times during the implementation process and at the end, the effectiveness of the chosen strategy is assessed. Progress can be measured by comparing the original lists of tasks and bottlenecks to the present situation. Interviewing operators again, using the questionnaire, may be helpful in finding the answer to the question: "Do the solutions really work?"

The only human behaviour that was not discussed in this deliverable is the behaviour of the emergency services. Their behaviour is part of Task 3.4 in the UPTUN project and will be described in deliverable 3.4.

REFERENCES

Advantica Technologies Ltd (2001) Joint industry project on carbon monoxide issues: Long-term reliability of domestic CO alarms, Final research report prepared for the Health and Safety Executive, Sheffield, UK. Contract Research Report 360/2001.

Amundsen, A.H. (1992) Driver behaviour in Norwegian road tunnels, 1st TUNNEL SAFETY CONFERENCE, p.315-326.

Andersson, M., Hedskog, B. & Nyman, H. (2002) Concept to improve the possibilities of escape from a single exit underground station, Proc. 4th Int. Conf. on Tunnel Fires, 2-4 Dec 2002, Basel, Switzerland.

Andersen, T. & Paaske, B. (2002) Fire safety in tunnels and selection of tunnel concept, 4th Int. Conf. on Tunnel Fires, 2-4 Dec 2002, Basel, Switzerland, p.199-208.

Ando, K., Ota, H. & Oki, T. (1988) Forecasting the flow of people (in Japanese), R.R.R. Railway Research Review, (45)8, p. 8-14.

Aqua Group (1984) Fire and Buildings, Granada Publishing Ltd, London.

Arnaudet, J-G. (1999) Analysis of tunnel fires. First International Conference Tunnel Fires and Escape from Tunnels, 5-7 May 1999, Lyon, France.

Ashe, B. & Hall, R. (1999) Prediction of evacuation from road tunnels. First International Conference Tunnel Fires and Escape from Tunnels, 5-7 May 1999, Lyon, France, p. 503-512.

Ashe, B. & Shields, T.J. (1998) Analysis and Modelling of the unannounced evacuation of a large retail store, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 291-300.

Bartley, S.H. (1938) Subjective brightness in relation to flash rate and the light-dark ratio, Journal of Experimental Psychology, 23(3), 1938, p. 313-319.

Barton, J. & Leather, J. (1995) Paxport – Passenger and Crowd Simulation, Passenger Terminal ’95, p. 71-77.

Batteau, D.W. (1967) The role of the pinna in human localization, Proceedings of the Royal Society 168, pp. 158-180.

Bellamy, L. (1989) Informative fire warning systems: a study of their effectiveness, Fire Surveyor, August 1989, p. 17-23.

Benthorn, L. & Frantzich, H. (1998) Fire Alarm in a Public Building: How Do People Evaluate Information and Choose Evacuation Exit? Human Behaviour in Fire, Proc 1st Int Symp, Shields, T.J. (Ed), University of Ulster, p. 213-222.

Berman, J. & Ody, K. (1995) Human factors and emergency response: the assessment of an integrated system, 2nd TUNNEL SAFETY CONFERENCE, p. 173-180.

Blauert, J. (1997) *Spatial Hearing* (Cambridge, MA: MIT Press).

Boer, L.C. (1998) Improved signposting/or the evacuation of passenger ships, Report TM-98-C081. Soesterberg (NL): TNO Human Factors.

Boer, L.C. (2002a) Behaviour by motorists on evacuation of a tunnel, Report TM-02-C034, TNO Human Factors, Soesterberg NL.

Boer L.C. (2002b) Finding your way out - Behaviour in emergency situations, TNO Traffic and Transport - Transport Matters, March 2002, p. 9, Soesterberg (NL).

Boer, L.C. (2003) Behavior of drivers during tunnel evacuation. In J. Saveur (ed.), (Re)Claiming the Underground Space (Lisse, NL; Abingdon, PA; Exton, PA; Tokyo: Balkema), p. 213-217.

Boer, L.C. & Skjong, R. (2001) Emergency evacuation: How better interior design can improve passenger flow, Paper, presented at "Cruise + Ferry 2001", London, 8-10 May 2001, 9p.

Boer, L.C. & van Wijngaarden, S.J. (2004) Directional sound evacuation from smoke-filled tunnels, Proceedings of the first International Symposium, Safe and Reliable Tunnels Innovative European Achievements, 4-6 February 2004, Prague, Czech Republic, p. 33-42.

Boer, L.C. & van Wijngaarden, S.J. (in press) Directional sound evacuation from smoke-filled tunnels. Ergonomics.

Boer, L.C., Wertheim, A.H., Ellens, E., Brisland , C.E.S. & Daanen, H.A.M. (1993) Ship listing: reactions of passengers, Report IZF 1993 C-26. Soesterberg (NL): TNO Human Factors

Boer, L.C., Winer, J. & Noren, A. (2004) Human Behaviour during Tunnel Evacuation: Basic Data, TNO report TM-04-D002.

Boer, L.C. & Withington, D.J. (2004) Auditory guidance in a Smoke-filled Tunnel. Ergonomics, 47, p. 1131-1140.

Boyce, K.E., Fraser-Mitchell, J.N. & Shields, T.J. (1998) Analysis and Modelling of an Office Evacuation Drill, Human Behaviour in Fire, Proc 1st Int Symp, Shields,TJ (Ed), University of Ulster, p. 691-702

Boyce, P.R. & Gamliel, A. (1992) The visibility of exit signs in smoke: A physical model. In: Proc. National Lighting Conference, Manchester, UK. April 5-8 1992.

Boyce, K.E., Shields, T.J. & Silcock, G.W.H. (1999a) Towards the characterisation of building occupancies for fire safety engineering: capabilities of disabled people moving horizontally and on an incline, Fire Technology 35(1), p. 51-67.

Boyce, K.E., Shields, T.J. & Silcock, G.W.H. (1999b) Towards the characterisation of building occupancies for fire safety engineering: prevalence, type, and mobility of disabled people, Fire Technology 35(1), p. 35-50.

Boyce, K.E., Shields, T.J., Silcock, G.W.H. (1999c) Towards the characterisation of building occupancies for fire safety engineering: capability of disabled people to negotiate doors, Fire Technology 35(1), p. 68-78.

Boyce, K.E., Shields, T.J., & Silcock, G.W.H. (1999) Towards the characterisation of building occupancies for fire safety engineering: capability of people with disabilities to read and locate exit signs, Fire Technology 35(1), p.79-86.

BRE (1993) Human Behaviour in Fire, BRE Digest 388, Nov 1993.

British Standards Institute (1989-1991) Fire Precautions in the Design, Construction and Use of Buildings. Part 2 (shops, 1989), Part 6 (places of assembly, 1991) and Part 10 (shopping complexes, 1991).

Bronkhorst, A.W. (1999) Interaction between signals in 3D auditory displays, Report TM-99-A026 [in Dutch], TNO Human Factors, Soesterberg NL.

Bryan, J.L. (1986) Damageability of buildings, contents and personnel from exposure to fire, Fire Safety Journal 11, p. 15-31.

Bryan, J.L. (1988) Behavioural response to fire and smoke, Chapter 1-16, SFPE Handbook of Fire Protection Engineering, pub. NFPA. 1st edition.

Bryan, J.L. (1998) Human Behaviour in Fire: The Development and Maturity of a Scholarly Study Area, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 3-12.

BS 5266 (1998) Part 2: Code of practice for electrical low mounted way guidance systems for emergency use. BSI, London.

BS 5266 (1999) Part 1: Emergency lighting. BSI, London.

BS7974 (2001) Standard for Fire Safety Engineering.

Bulman, E. & Clifford, P. (1995) Customer Service. Interchangable?, Passenger Terminal World, p.18-23.

Buckmann, L.T. & Leather, J.A. (1994) Modelling Station Congestion the PEDROUTE Way, Traffic Engineering and Control, 35(6), June 1994, p. 373-377.

Canter, D. (1980-1981), Fires and human behaviour: emerging issues, Fire Safety Journal 3, p. 41-46.

Canter, D. (1990) Fires and Human Behaviour, 2nd edition, pub. David Fulton, London.

Canter, D., Donald, I. & Chalk, J. (1995) Pedestrian behaviour during emergencies underground: The psychology of crowd control under life-threatening circumstances, Proc. 2nd Int. Conf. on Safety in Road and Rail Tunnels, 3-6 April, Granada, Spain, p. 135-150.

Cappuchio, J, (2000) Pathfinder: A computer-based, timed egress simulation, Fire Protection Engineering, Fall 2000, p. 11-12.

Carlile, S. & King, A.J. (1993) Auditory neuroscience: from outer ear to virtual space, Current Biology, 3, 1993, p. 446-448.

Chan, R. & McCleery, J. (1995) Human Factors, 2nd TUNNEL SAFETY CONFERENCE, p. 163-172.

Charters, D.A., Gray, W.A. & McIntosh, A.C. (1994) A computer model to assess fire hazards in tunnels (FASIT), Fire Technology, 1st quarter 1994, p.134-154.

Clements, P.A. & Gillespie, D. (1995) Egress constraints on occupants when subjected to radiant energy, SFPE September Conference, Orlando, USA, p. 209-214.

Clung , C. (2002) Tunnel Rescue-A Systematic Approach, Fire & Rescue, July 2002.

COB/RWS Centre for Tunnel Safety (2004) Guideline Scenario analysis, Part 1: Incidents in road tunnels (Only available in Dutch (Leidraad Scenarioanalyse).

Collins, B.L. (1991) Visibility of exit signs and directional indicators, Journal of the Illuminating Engineering Society. 20(1), p. 117-1133.

Collins, B.L. et al (1990) Evaluation of exit signs in clear and smoke conditions, National Institute of Standards and Technology, Report NISTIR 4399, Gaithersburg, MD, USA.

Collins, B.L. et al (1992) Visibility of exit signs in clear and smoky conditions, Journal of the Illuminating Engineering Society. 21(1), p. 69-84.

Colombo, A.G. (2001) "Lessons learnt from Tunnel Accidents", in the framework of the NEDIES project.

Conti, R.S. et al (1999) An overview of technology and training simulations for mine rescue teams, Proceedings of the 28th International Conference of Safety in Mines Research Institutes (Sinaia, Romania). Vol. II, p. 521-538.

Conti, R.S. & Chasko, L.L. (2001), Technologies for today’s mine emergency responders, International Journal of Emergency Management, 1(1), 2001, p. 13-29.

Curtat, M. (1998) Fire Safety software to optimise human evacuation, CSTB Recherche Information letter no.37 (June 1998).

De Vos, A. P., Hoekstra, W. & Pieterse, M. T. J. (1998). The effect of acceleration cuing on braking behaviour in a driving simulator (Report TM-98-A066). Soesterberg, The Netherlands: TNO Human Factors Research Institute.

Dhar, B.B. (1997) Global trends in development of mine safety technology: A need for international collaboration.Proceedings 27th International Conference of Safety in Mines Research Institutes, New Delhi, India, 20th-22nd February 1997, p. 3-13.

Dickson, M. (1993) Strategies and Methods for Appraising Existing Stands, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 1-11.

Directional sound evacuation: Marine trials, data and analysis (June and October 2001, updated 14 May 2002) [CD]. Southampton, UK: Maritime & Cost Guard Agency.

Dobroski, J.R. & Conti, R.S. (1991) A review of distributed temperature sensing for underground belt lines, Proceedings of 6th International Longwall Mining Conference. Pittsburgh, USA, 1991, 13pp.

Donegan, H.A., Pollock, A.J. & Taylor, I.R. (1994) Egress complexity of a building, Fire Safety Science, Proc 4th Int Symp IAFSS, p. 601-612.

Donegan, H.A. & Taylor, I.R. (1998) How Complex is the Egress Capability of Your Design?, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 601-610.

Ebihara, M., Ohtsuki, A. & Iwaki, H. (1992) Model for simulating human behaviour during emergency evacuation based on classificatory reasoning and certainty value handling, Shimizu Technical Research Bulletin,Tokyo, Japan no.11 (March 1992) p. 27-33.

Edelman, P. et al (1980) A model of behaviour in fires applied to a nursing home fire, In D. Canter (Ed.) Fires and human behaviour, p. 181-203. London: Wiley.

Fahy, R.F. (1991) EXIT89: An evacuation model for high-rise buildings, Fire Safety Science - Proc. 3rd Int. Symp., p. 815-823.

Fahy, R.F. (1993a) EXIT89: An evacuation model for high-rise buildings, Proc. Interflam ’93, p. 519-528.

Fahy, R. (1993b) Building Fire Simulation Model, Fire Journal (July 1993), p. 93-105.

Fahy, R.F. (1994) EXIT 89 - An evacuation model for high-rise buildings - Model description and example applications, Fire Safety Science - Proc. 4th Int. Symp., p. 657-668.

Fahy, R.F. (1996) EXIT 89 - high-rise evacuation model – recent enhancements and example applications, Proc. Interflam ’96, p. 1001-1006.

Fahy, R.F. (1998) A practical example of an evacuation model for complex spaces, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 743-752.

Fahy, R. (2001) Verifying the predictive capability of EXIT89, Human Behaviour in Fire, Proc 2nd Int Symp, MIT, pub. Interscience Communications Ltd, p. 53-64.

Fahy, R.F. & Proulx, G. (1995) Collective Common Sense: A Study of Human Behaviour During the World Trade Centre Evacuation, NFPA Journal March/April (1995), p. 59-67.

Feinberg, W.E. & Johnson N.R. (2001) Primary group size and fatality risk in a fire disaster, Proc. 2nd Int. Symp.on Human Behaviour in Fire 2001, Massachusetts Institute of Technology, Cambridge, Boston, USA, 26-28 March 2001, pp 11-22, Pub.: Interscience Communications, London.

Feinberg, W.E. & Johnson, N.R. (1998) Queuing, Exit-Sorting and Evacuation in Fire Emergencies: A computer simulation investigation, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 721-730.

Fennrup, S.O. (2002) Tunnel Firefighting, Fire&Rescue, July 2002.

Fermaud, C., Jenne, P. & Muller, W. (1995) Fire in a commuter train – rescue procedures as perceived by passengers, 2nd TUNNEL SAFETY CONFERENCE, p. 181-188.

Fire International (2001) Blazing Inferno beneath Baltimore city, Fire International , November 2001.

Fire Prevention, 320, May 1999, p. 8.

Fire and flammability bulletin, May 1999

Fraser-Mitchell, J.N. (1994) An Object-Oriented Simulation (CRISP 2) for Fire Risk Assessment, Fire Safety Science, Proc 4th Int Symp IAFSS, p. 793-804.

Fraser-Mitchell, J.N. (1996) Lessons Learnt During The Development Of CRISP2, A Monte-Carlo Simulation For Fire Risk Assessment, Proc 7th Intl. Fire Conf., INTERFLAM '96, ed. Franks,C, Interscience Communications Ltd, London, p. 631-639.

Fraser-Mitchell, J.N. (1997) Risk Assessment Of Factors Relating To Fire Protection In Dwellings, Fire Safety Science, Proc 5th Int Symp IAFSS, p. 631.

Fraser-Mitchell, J.N. (1998) Modelling Human Behaviour within the Fire Risk Assessment Tool CRISP, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 445-457.

Fraser-Mitchell, J.N. (1999) Modelling Human Behaviour within the Fire Risk Assessment Tool CRISP, Fire & Materials 23, p. 349-355.

Fraser-Mitchell, J.N. (2000) CRISP User manual, BRE Client Report 76829, (July 2000).

Fraser-Mitchell, J.N. (2001) Simulated Evacuations of an Airport Terminal Building, using the CRISP model, Human Behaviour in Fire, Proc 2nd Int Symp, MIT, pub. Interscience Communications Ltd, 2001.

Fraser-Mitchell, J.N. (2003) Human Behaviour and Egress Modelling for Fire Safety in Tunnels, BRE Client Report CR 212414, 2003.

Fraser-Mitchell, J. (2003) Demonstration of CRISP applied to a tunnel fire, given to G. Khoury in Feb 2003.

French, S. & Stevens, T. (1999) Principles for the detrainment and evacuation of Heathrow Express Trains, Proc. 2nd Int. Conf. on Tunnel Management, Operation and Maintenance, 16-17 Feb 1999, Hong Kong, pub. ITC Ltd, p. 283-293.

Friedman, R. (1991) Survey of computer models for fire and smoke, Prepared for FORUM for international cooperation on fire research, December 1991.

Galea, E. & Gwynne, S. (2001) Evacuating an overturned smoke-filled rail carriage, Human Behaviour in Fire, Proc 2nd Int Symp, MIT, pub. Interscience Communications Ltd, p. 135-146.

Galea, E.R. & Perez Galparsoro, J.M. (1994) A computer-based simulation for the prediction of evacuation from mass-transport vehicles, Fire Safety Journal 22 (1994) p. 341-366.

Galea, E.R., Gwynne, S., Owen, M., Lawrence, P.J. & Philippidis, L. (1998) Comparison of the predictions from the building EXODUS evacuation model with experimental data, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 711-720.

Geake, E. (1993) Lessons from the inferno, New Scientist supplement FIRE (17 April 1993).

Gillard, J. & Arch, P. (1995) Mersey Tunnels Kingsway Tunnel fire incident 15 October 1994, 2nd TUNNEL SAFETY CONFERENCE, p. 97-106.

Grace, T. (2001) On the use of voice alarm systems, Proc. 2nd Int. Symp.on Human Behaviour in Fire 2001, Massachusetts Institute of Technology, Cambridge, Boston, USA, 26-28 March 2001, pp 185-196, Pub.: Interscience Communications, London.

Gray, D. & Varkevisser, J. (1995) The Huguenot Toll Tunnel Fire, 2nd TUNNEL SAFETY CONFERENCE, p. 57-66.

Groner, N.E. (1993) More on wayfinding in buildings, Letter to NFPA Journal, Sept/Oct 1993 p. 8-9.

Gross, H.G. (1986) Visibility threshold range observations of LED emergency egress lighting strips and signs through dense smoke and turbid water. In: Proceedings of the Twenty-third Annual Symposium SAFE Association. Las Vegas, NV, USA, December 1-5 1986.

Gross, H.G. (1987) Koch emergency egress lighting systems for adverse optical conditions for military and commercial aircraft and other applications. In: Proceedings of the Twenty-fourth Annual Symposium SAFE Association. San Antonio, TX, USA, Dec 11-13 1987.

Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J. & Philippidis, L. (1998) A review of the methodologies used in the computer simulation of evacuation from the built environment, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 681-690.

Gwynne, S., Galea, E.R., Lawrence, P.J., Owen, M. & Philippidis, L. (1999) Adaptive decision-making in buildingEXODUS in response to exit congestion, Proc 6th Int Symp IAFSS, p. 1041-1052.

Gwynne, S., Galea, E.R., Lawrence, P.J., & Philippidis, L. (2001) Simulating occupant interaction with smoke using building EXODUS, Human Behaviour in Fire, Proc 2nd Int Symp, MIT, pub. Interscience Communications Ltd, p. 101-110.

Haas, E.C. & Edworthy, J. (1996) Designing urgency into auditory warnings using pitch, speed and loudness, Computing and Control Engineering Journal, August 1996, p. 193-198.

Hankin and Wright (1958) London Transport Executive, Passenger flow in subways and on staircases, Engineering, August 22, p. 245.

Hart, S.G. & Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In: P. A. Hancock and Meshkati (Eds.).

Hartzell, G.E. (1998) Engineering Analysis of Hazards to Life Safety in Fires: The Fire Effluent Toxicity Component, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields, T.J., University of Ulster, p. 621-630.

Helbing, D., Farkas, I. & Vlcsek, T. (2000) Simulating dynamical features of escape panic, Nature vol.407 (28 Sept 2000), p. 487-490.

Heskestad, A.W. (1999) Performance in smoke of wayguidance systems, Fire and Materials 23(6), p. 375-381.

Heskestad, A.W. & Pedersen, K.S. (1998) Escape through smoke: Assessment of human behaviour and performance of wayguidance systems, Proc. 1st Int. Symp. on Human Behaviour in Fire, Belfast, 31 August- 2 September 1998, p. 631-638.

Hill, N.E.G. (1947) The recognition of coloured light signals which are near the limit of visibility, Proc. Phys. Soc. (London), 59(4), p. 560-574.

Hodgson, P. (1993) The trials of designing a safe means of escape, Fire Prevention 259 (May 1993) p.20-23.

Hogema, J.H. & Hoekstra, W. (1998). Description of the TNO Driving Simulator (Report TM-98-D007). Soesterberg: TNO Technische Menskunde.

Hogema, J.H., Hoekstra, W. & Verschuren, R.M.A.F. (2003). A driving simulator vehicle model with an extended steering system submodel (TNO Report TM-03-D004). Soesterberg: TNO Technische Menskunde.

Home Office (1990) The Guide to Safety in Sports Grounds, HMSO, London, 4th Edition.

Home Office (1993) Home Office project looks at winds effect on escape times, Fire (July 1993) p.24.

ICCL (2000) Recommendations on evacuation analysis for passenger ships and high-speed passenger craft, Passenger vessel evacuation analysis, IMO document FP 45/3/1.

ICNIRP (1999) ICNIRP Statement on laser pointers, International Commission on Non-Ionizing Radiation Protection, Standing Committee IV, 1999.

IMO, International Maritime Organisation (1993) Guidelines on evaluation, testing and application of low-location lighting on passenger ships, MSC 62/WP.17, IMO, Washington USA.

Institution of Structural Engineers (1989) Safety Considerations for the Design and Erection of Demountable Grandstands, London.

Interscience Communications (2001), Proc. 2nd Int. Symp.on Human Behaviour in Fire 2001, Massachusetts Institute of Technology, Cambridge, Boston, USA, 26-28 March 2001, Pub.: Interscience Communications, London.

ISO 7029 (1984) Acoustics—Threshold of hearing by air conduction as a function of age and sex for otologically normal persons (Genève: International Organisation for Standardization).

Jenssen, G. (1993a) Evacuating in smoke: Full scale tests on emergency egress information systems and human behaviour in smoky conditions, Report, IGP AS, Trondheim, Norway.

Jenssen, G. (1993b) Norwegian research shows usefulness to blind of "notched rail" in fires, Fire (July 1993) p.27 & 30.

Jin, T. (1997) Studies on human behavior and tenability in fire smoke. Fire Safety Science—Proceedings of the fifth international symposium, p. 3-21.

Jin, T. & Yamada, T. (1985) Irritating effects of fire smoke on visibility, Fire Science & Technology, vol.5 no.1, p. 79-90.

Jones, B.K. & Hewitt, J.A. (1985) Leadership and group formation in high-rise building evacuations, Fire Safety Science: Proc 1st Int Symp., p. 513-522.

Judge, B. (1993) Egress analysis and risk assessment made real, Fire International 138 (Feb 1993), p. 45-46.

Kakegawa, S., Yashiro, Y., Ebihara, M. & Ohtsuki, A. (1994) Evaluation of Fire Safety Measures in Care Facilities for the Elderly by Simulating Evacuation Behavior, Fire Safety Science, Proc 4th Int Symp IAFSS, p. 645-656.

Kelly, D.H. (1969) Flickering patterns and lateral inhibition, J. Opt. Soc. Am., 59(10), 1969, p. 1361-1370.

Kendik, E. (1984) GLC code of practice "Means of escape in case of fire" - a comparison with a design method for calculating pedestrian movement, Fire Safety Journal 7, p. 199-201.

Kendik, E. (1985a) Assessment of escape routes in buildings and a design method for calculating pedestrian movement, SFPE Technology Report 85-4.

Kendik, E. (1985b) Methods of design for means of egress: towards a quantitative comparison of national code requirements, Fire Safety Science - Proc. 1st Int. Symp., p. 497-511.

Kennedy, W., Harvey, N. & Li, S. (2001) Comparison of N. F. P. A. 130 station emergency exiting calculations with SIMULEX emergency exiting software, Proc 3rd Int. Conf. on Tunnel Fires and Escape from Tunnels, 9-11 Oct 2001, Washington DC, USA.

Ketchell, N., Cole, S.S. & Webber, D.M. (1993) The EGRESS code for human movement and behaviour in an emergency environment, Engineering For Crowd Safety, ed. Smith, RA & Dickie, JF pub. Elsevier Science BV, p. 361-370.

Ketchell, N. (2001) Private communication (lecture at Greenwich University Egress Modelling Course).

Ketchell, N., Bamford, G.J. & Kandola, B. (1995) Evacuation modelling: A new approach, Proc. Asiaflam ’95, p. 499-505.

Khoury, G.A. (2003) EU tunnel fire safety action, Tunnels and Tunnelling International, April 2003, p. 20-23.

Kisko, T.M. & Francis, R.L. (1985) Evacnet+: A computer program to determine optimal evacuation plans, Fire Safety Journal 9, p. 211-220.

Klote, J.H. (1993) A method for calculation of elevator evacuation time, J. of Fire Prot. Engineering vol.5 no.3, p. 83-95.

Kostreva, M.M. (1994) Mathematical modelling of human egress from fires in residential buildings (collected papers), NIST report NIST-GCR-94-643.

Kostreva, M.M. & Lancaster, L.C. (1998) A comparison of two methodologies in HAZARD I fire egress analysis, Fire Technology 34(3), p. 227-243.

Kostreva, M.M., Wiecek, M.M. & Getachew, T. (1991) Optimisation models in fire risk analysis for residential buildings, Fire Safety Science - Proc. 3rd Int. Symp., p. 805-814.

Krul, A.J. & Boer, L.C. (2002) Knowledge of emergency provisions in road tunnels [in Dutch], Report TM-02-C008, TNO Human Factors, Soesterberg NL.

Kuipers, M. (1996) Private Communication (Human Behaviour During Escape From Accidental Fire in Buildings - Case Studies, Writewell Research.

Lagadec, P. (2003) “Faire face à l’imprévisible”, La recherche, oct 2003.

Langendijk, E.H.A. (2002) Spectral Cues of Spatial Hearing doctoral dissertation (Delft NL: University of Technology).

Langendijk, E.H.A. & Bronkhorst, A.W. (2002) Contribution of spectral cues to human sound localization, Journal of the Acoustical Society of America, 112, p. 1583-1596.

Legislative Council Panel on Transport (2000), Fire Incident at the Cross Harbour Tunnel on 29 May 2000, Hong Kong.

Levin, B. (1989a) EXITT – A simulation of occupant decisions and actions in residential fires, Fire Safety Science - Proc. 2nd Int. Symp., p. 561-570.

Levin, B. (1989b) EXITT – A simulation of occupant decisions and actions in residential fires: User’s guide and program description, NBSR 87-3591, NBS.

Lieberman, P., Protopapas, A., Reed, E., Youngs, J.W. & Kanki, B.G. (1994) Cognitive defects at altitude, Nature v.372 (24 November 1994) p. 325.

Lindley, J. (1997) The Summit Tunnel Incident, I.Chem.E. Loss Prevention Bulletin 134, p. 14-18.

Lischer, M. (1993) The Impact of Facility Design on Crowd Flow, Comfort and Safety, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 343-349.

Lo, S.M., Yuen, K.K., Lu, J. & Fang, Z. (2001) A possibility measure method for predicting wayfinding patterns of evacuees under fire situations. Proc. 2nd Int. Symp.on Human Behaviour in Fire 2001, Massachusetts Institute of Technology, Cambridge, Boston, USA, 26-28 March 2001, pp 363-372, Pub.: Interscience Communications, London.

Lo, S.M. & Fang, Z. (2000) A spatial-grid evacuation model for buildings, J. Fire Sciences 18, p. 376-394.

London Transport (1989) Jubilee Line Extension – Design Guidelines (Draft – revision 5), London.

Makous J.C. & Middlebrooks J.C. (1990) Two-dimensional sound localization by human listeners, Journal of the Acoustical Society of America, 87, p. 2188-2200.

Malhotra, H.L. (1984) Escape travel distances need a more rational approach, FIRE, November 1984 p. 16-18.

Mandetta, S. (1993) Spectators in sports facilities – the prospects of a European regulation, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 187-193.

Marchant, R . (1999) private communication (e-mail dated 2nd of December 1999).

Marsden, A. (1999) Escape from tunnels - human behaviour. Are evacuation exercises realistic? 1st Int Conf. Tunnel Fires and Escape from Tunnels, 5-7 May 1999, Lyon, France, p. 551-556.

McLean, G.A. (2001) Access-to-egress: A meta-analysis of the factors that control emergency evacuation through the transport airplane type-III overwing exit, U.S. Department of Transportation, Federal Aviation Administration, Final Report DOT/FAA/AM-01/2, January 2001, 32p.

Melinek, S.J. & Booth, S. (1975) An analysis of evacuation times and the movement of crowds in buildings, BRE Current Paper CP 96/75.

Moller-Hansen, J. (2002) Efficient self rescue of tunnel users by use of intelligent exit signs, 4th Int. Conf. on Tunnel Fires, 2-4 Dec 2002, Basel, Switzerland, p. 247-256.

Mont Blanc tunnel fire investigation (1999) Tunnel management international magazine, June 1999, p.6.

Mutani, G. & Cali, M. (1998) A model for people evacuation, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields, T.J., University of Ulster, p. 731-742.

Neerincx, M.A. (2003) Cognitive task load design: model, methods and examples. In: E. Hollnagel (ed.), Handbook of Cognitive Task Design. Chapter 13. Mahwah, NJ: Lawrence Erlbaum Associates.

Nelson, H.E. & MacLennan, H.A. (1988) Emergency Movement, in the SFPE Handbook for Fire Protection Engineering (1st edn, DiNenno, P.), National Fire Protection Association, Quincy, MA., p. 2106-2115.

New ASTM toxic potency standard (1995) Fire & Flammability Bulletin, March 1995, p. 6-7.

Newman, D.G., Rhodes, N.& Locke, H.A. (1998) Simulation versus code methods for predicting airport evacuation, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 519-528.

Okasaki, S. & Matsushita, S. (1993) A study of simulation model for pedestrian movement with evacuation and queuing, Engineering For Crowd Safety, ed. Smith, RA & Dickie, JF pub. Elsevier Science BV, p. 271-280.

Older, S.J. (1964) Pedestrians, Dept. Scientific & Industrial Research, Road Research Laboratory, LN 275/SJO, Crowthorne, England.

O'Leary, T.J. & Gratz, J.M. (1982) An analysis of fire evacuation procedures using simulation, Fire Journal (May 1982) p. 119-126.

Olsson, P.A. & Regan, M.A. (1998) A Comparison between actual and predicted evacuation times, 1st Int. Symp. On Human Behaviour In Fire, University of Ulster, p. 479.

Owen, M., Galea, E.R. & Lawrence, P.J. (1996) The EXODUS evacuation model applied to building evacuation scenarios, J. of Fire Prot. Engr. 8(2), p. 65-86.

Owen, M., Galea, E.R. & Lawrence, P.J. (1997) Advanced Occupant Behavioural Features of the building-EXODUS Evacuation Model, Proc 5th Int Symp IAFSS, p. 795-806.

Ozel, F. (1992) Simulation modelling of human behaviour in buildings, Simulation, p. 377-384.

Papaioannou, P. & Georgiou, G. (2003) Human behaviour in tunnel accidents and incidents: end-users, operators and response teams (UPTUN Deliverable 3.2).

Pauls, J. (1987) Calculating evacuation times for tall buildings, Fire Safety Journal 12, p. 213-236.

Pauls, J. (1988) Movement of people, Chapter 1-15, SFPE Handbook of Fire Protection Engineering, pub. NFPA. 1st edition.

Paulsen, T. (1994) The effect of escape route information on mobility and wayfinding under smoke logged conditions. Proc. 4th International Symposium, International Association for Fire Safety Science. Ottawa, 1994, p. 693-704.

Pearson, R.G. & Joost, M.G. (1983) Egress Behaviour Response times of handicapped and elderly subjects to simulated residential fire situations, NBS-GCR-83-429.

Peter, F. (2004) Causes, effects and control of real tunnel fires, March 2000, Internet Prüfstelle (http://www.pruefstelle.at/Vortrag_7.html).

Petrovitsch, H. (2000) Disaster on Austrian Funicular, Today's railways, No 61, p. 6.

Phillips, H.R. et al (1997) An integrated approach to post-incident survival strategy, Proceedings of International Conference on Coal Research, Technical Session: ‘Underground Coal Mining - Productivity and Safety’, Calgary, Canada, September1997, p. 167-178.

PIARC (2004) Good practice for the operation and maintenance of road tunnels (PIARC / AIPCR WG1, 2004).

Pigott, B.B. (1988) Fire Detection and Human Behaviour, Fire Safety Science - Proc. 2nd Int. Symp., p. 573-582.

Pigott, B.B. (1993) Fire intelligence – the key to economical means of escape, Proc 6th Intl. Fire Conf., INTERFLAM '93, ed. Franks,C, Interscience Communications Ltd, London, p.181-188.

Pigott, B.B. (1998) An Administrator’s View of Human Behavioural Research from 1975 to 1995, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 31-38.

Polus, A., Schofer, J.L. & Ushpiz, A. (1983) Pedestrian Flow and Level of Service, Journal of Transportation Engineering, Proc. ASCE 109, p. 46-57.

Poon, L.S. (1994) EvacSim: a simulation model of occupants with behavioural attributes in emergency evacuation of high-rise building fires, Proc 4th Int Symp IAFSS, p. 681-692.

Poon, L.S. (1995) Numerical modelling of human behaviour during egress in multi-storey office building fire as using "EvacSim" - some validation studies, Proc. Asiflam ‘95, p. 163-174.

Poon, L.S. (2000) Simulation of fire development and occupant interaction in buildings, PhD thesis, Victoria University of Technology.

Poyner, B., Robinson, D., Hughes, N. & Ayles, P. (1972) Safety in football stadia: a method of assessment, Scientific Control Systems (SCICON), London.

Powell, S. & Grubits, S. (1999) Tunnel design with TRAFFIC - tunnel risk assessment for fire incidents and catastrophes, Proc. 1st Int. Conf. on Tunnel Fires & Escape from Tunnels, 5-7 May 1999, Lyon, France, p. 61-72.

Predtechenskii, V.M. & Milinskii, A.I. (1978) Planning for foot traffic flow in buildings, Amerind Publishing Co. Pvt. Ltd, New Delhi (translated from Russian).

Proulx, G. (1993) A stress model for people facing a fire, Journal of Environmental Psychology 13, 000-000 (ie, preprint).

Proulx, G. (1995) Evacuation time and movement in apartment buildings, Fire Safety Journal 24, p. 229-246.

Projector, T.E. (1957) Effective intensity of flashing lights, Illum. Eng., 52(12), 1957, p. 630-640.

Proulx, G. et al (1999) Assessment of photoluminescent material during office occupant evacuation, Internal Report 774. Ottawa (CA): Institute for Research in Construction, National Research Council.

Proulx, G. & Sime, J.D. (1991) To prevent 'panic' in an underground emergency: why not tell people the truth?, Fire Safety Science - Proc. 3rd Int. Symp., p. 843-852.

Purser, D.A. (1988) Toxicity Assessment, Chapter 1-14, SFPE Handbook of Fire Protection Engineering, pub. NFPA. 1st edition.

Purser, D. (1989) Modelling time to incapacitation and death from toxic and physical hazards in aircraft fires, AGARD No 467, p. 41-1 - 41-12.

Purser, D.A. (1998) Quantification of Behaviour for Engineering Design Standards and Escape Time Calculations, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 497-508.

Purser, D. (in press) GridFlow: An object-orientated building evacuation model combining pre-movement and movement behaviours for performance-based design. Paper presented at 7th IAFSS symposium for Fire Safey Science. Held 16-21 June 2002, Massachusetts, USA.

Purser, D.A. & Berrill, K.R. (1983) Effects of carbon monoxide on behaviour in monkeys in relation to human fire hazard, Archives of Environmental Health, vol 38 no 5, September/October 1983, p. 308-315.

Rasmussen, J. (1986) Information processing and human-machine interaction: An approach to cognitive engineering (Elsevier, Amsterdam).

Reisser-Weston, E. (1996) Simulating human behaviour in emergency situations, RINA, Int. Conf. of Escape, Fire & Rescue, 19/20 Nov 1996.

Rhodes, N. (1999) Combining smoke simulation and evacuation modelling. An attempt to clarify the first actions in an emergency, Proc. 1st Int. Conf. on Tunnel Fires and Escape from Tunnels, 5-7 May 1999, Lyon, France, p. 513-518.

Rhodes, N. & Wong, H. (2001) Faster and safer evacuation by designing for behavioural trends, 3rd Int Conf. Tunnel Fires and Escape from Tunnels, 9-11 Oct 2001, Washington DC, USA, p. 435.

Roberts, A.F. (1988) Strategy for assessing fire protection in mines, Fire Engineers Journal, March 1988, p. 13-17.

Rose, J. & Harding, B. (1993) Monitoring, analysis and management of safe operations in a high-capacity tunnel Metro, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 351-359.

Rubadiri, L. & Roberts, J.P. (1994) Evacuating workers with disabilities, Health and Safety Practitioner, May 1994 p. 21-24.

Rutherford, P. & Withington, D.J. (1998) Sound location for aiding emergency egress, Fire Safety Engineering, 5, p. 14-17.

RWS Centre for Tunnel Safety (2002) Dutch standard contingency plan for road tunnels. Summary in English available on the website: www.tunnelsafety.nl.

Rypkema, J.A., Ruijsendaal, M., van den Bosch, K., Schraagen, J.M.C. & Holewijn, M. (2002) Mentale belasting operator Westerscheldetunnel (TNO report TM-02-C039) TNO Human Factors, Soesterberg, NL.

Saunders, W. (1996) Occupant decision making in office building fires: A methodology for data collection, Proc 7th Intl. Fire Conf., INTERFLAM '96, ed. Franks,C, Interscience Communications Ltd, London, p. 741-752.

Schneider, V. (2001) Application of the individual-based evacuation model ASERI in designing safety concepts, Human Behaviour in Fire, Proc 2nd Int Symp, MIT, pub. Interscience Communications Ltd, p. 41-52.

Shestopal, V.O. & Grubits, S. (1994) Evacuation Model for Merging Traffic Flows in Multi-Room and Multi-Storey Buildings, Fire Safety Science, Proc 4th Int Symp IAFSS, p. 625-632.

Shields, T.J. & Boyce, K.E. (1995) Emergency egress capabilities of people with mixed abilities, in A.E. Vardy (ed.), *Safety in road tunnels* (Kempston: Independent Technical Conference Ltd), p. 347-353.

Shipp, M. (2001) private communication (e-mail dated 3rd of May 2001).

Sime, J.D. (1984a) Escape Behaviour in fires: 'panic' or affiliation?, PhD thesis, Department of Psychology, University of Surrey.

Sime, J.D. (1984b) Perceived Time Available: The Margin of Safety in Fires, Fire Safety Science - Proc. 1st Int. Symp., p. 561-570.

Sime, J. (1992) Human Behaviour in Fires, Summary Report, JSA Research Consultants, Research Report 45, Joint Committee on Fire Research.

Sime, J. (1993) Crowd Psychology and Engineering: Designing for People or Ballbearings? Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 119-131.

Sime, J. (1996) Assessing the occupant response safety factor in evacuation time calculations, Proc 7th Intl. Fire Conf., INTERFLAM '96, ed. Franks,C, Interscience Communications Ltd, London, p..763.

Sime, J.D. (1998) An Occupant Response Escape Time (ORET) model, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 299-308.

Sime, J., Breaux, J. & Canter, D. (1994) Human behaviour patterns in domestic and hospital fires, Building Research Establishment Occasional Paper OP59, A99B, 1 (LRO).

Smith, W. & Dowell, J. (2000) A case study of co-ordinative decision-making in disaster management", Ergonomics, vol 43, n° 8.

Stahl, F.I. (1982) BFIRES-II: A behaviour-based computer simulation of emergency egress during fires, Fire Technology 18(1), p. 49-65.

Stanton, R.J.C. & Wanless, G.K. (1993) Pedestrian Movement, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 71-79.

Still, G.K. (1993) New computer system can predict human response to building fires, FIRE, vol 84, p.40-41 (Jan 1993).

Still, G.K. (1994) Simulating Egress using Virtual Reality – A Perspective View of Simulation and Design, Paper 25, IMAS 94, Fire Safety on Ships, 26-27 May, 1994.

Still, G.K. (2000) Crowd Dynamics, PhD Thesis, University of Warwick, August 2000. The thesis is available online from http://www.crowddynamics.com/Thesis/Contents.htm.

Takahashi, K., Tanaka, T. & Kose, S. (1989) A Evacuation Model for use in Fire Safety Design of Buildings, Fire Safety Science, Proc 2nd IAFSS, p. 551-560.

Taylor, I.R. (1996) A revised interface for EVACNET+, Proc. Interflam '96, p. 1013-1019.

Thompson, P.A. & Marchant, E.W. (1993) Modelling Techniques for Evacuation, Engineering for Crowd Safety, ed. Smith, RA & Dickie, JF, pub. Elsevier Science BV, p. 259-269.

Thompson, P.A. & Marchant, E.W. (1994) Simulex: Developing New Techniques for Modelling Evacuation, Proc 4th Int Symp IAFSS, p. 613-624.

Thompson, P.A. & Marchant, E.W. (1995a) A computer model for the evacuation of large building populations, Fire Safety Journal 24, p. 131-148.

Thompson, P.A. & Marchant, E.W. (1995b) Testing and application of the computer model "SIMULEX", Fire Safety Journal 24, p. 149-166.

Thompson, P., Wu, J. & Marchant, E.W. (1997) "Simulex 3.0: Modelling Evacuation in Multi-Storey Buildings" Proc 5th Int Symp IAFSS, p. 725-736.

Thompson, P.A., Wu, J. & Marchant, E.W. (1996) Modelling Evacuation in Multi-storey Buildings with Simulex, Fire Engineers Journal (vol. 56, no. 185), November 1996, p. 6-11.

Tong, D. & Canter, D. (1985) The decision to evacuate: a study of the motivations which contribute to evacuation in the event of fire, Fire Safety Journal 9, p. 257-265.

Toshiyuki, A. (1993) Prediction System of Passenger Flow, Engineering For Crowd Safety, ed. Smith, RA & Dickie, JF pub. Elsevier Science BV, p. 249-258.

Tunnel Management International (2000), September 2000.

Turner, R.H. & Killian, L.M. (1957) Collective Behaviour, Prentice Hall, Englewood Cliffs, NJ.

Various sources, Contributed by Cliff Barnett. Extract from: http://www.civil.canterbury.ac.nz/sfpe/newsletters/45s1-1.shtml.

Watts, J.M. jr (1987) Computer models for evacuation analysis, Fire Safety Journal 12, p. 237-245.

Weick, K. (1993) « The collapse of sensemaking in organizations: The Mann Gulch disaster » E Administrative Science Quarterly; Dec 1993.

Wenkman, H., Lehtimaki, S. & Mannikko, S. (1998) Evacuation of a theatre: Exercise vs calculations, 1st Int. Symp. On Human Behaviour In Fire, University of Ulster, p. 479.

Wesley Grantham, D. (1995) Spatial hearing and Related Phenomena, in B.C.J. Moore (ed.), *Hearing* (Academic Press, San Diego), p. 297-345.

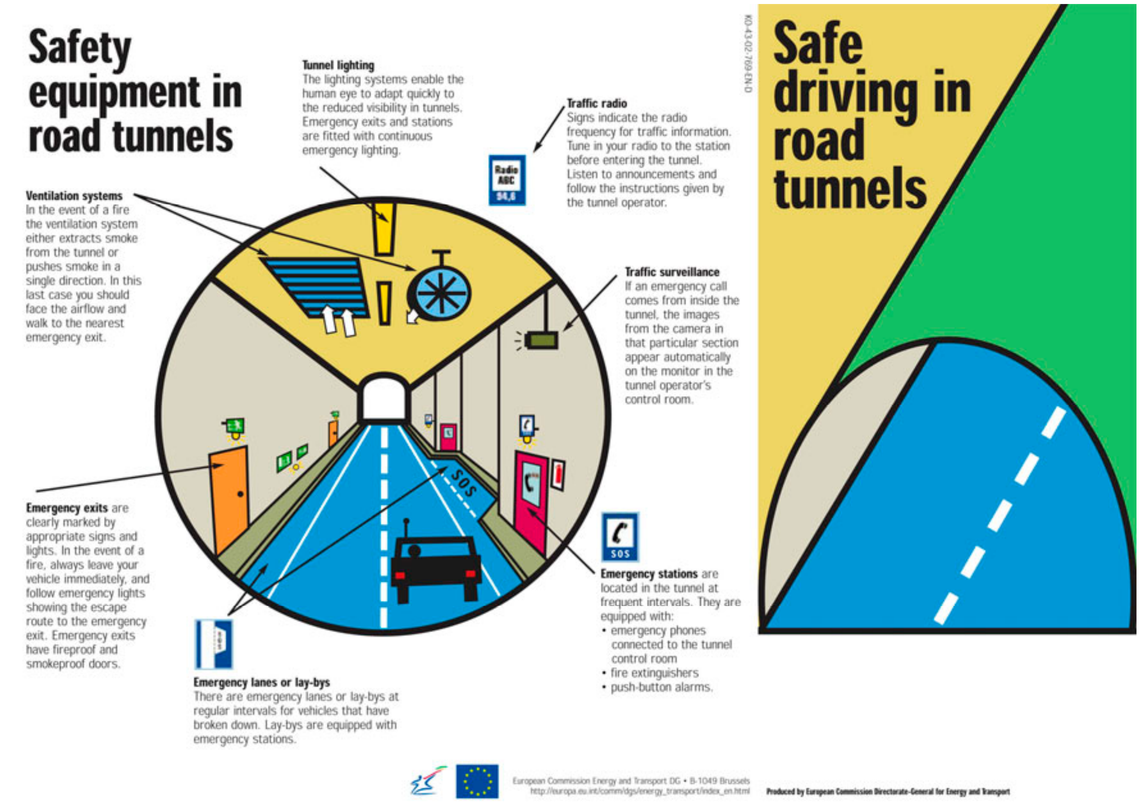
Withington, D.J. (2002) Life saving applications of directional sound, in M. Schreckenberg & S.D. Sharma (eds.), *Pedestrian and Evacuation Dynamics* (Berlin/New York: Springer), p. 277-296.

Wood, P.G. (1972) The behaviour of people in fires. Fire Research Note FR953, Fire Research Station. Loughborough University of Technology, Dept of Social Sciences & Economics, Dept of Ergonomics & Cybernetics.

Yoshida, Y. (1995) Evaluating building fire safety through egress prediction: a standard application in Japan, Fire Technology, 2nd quarter 1995, p. 158-174.

Zhao, L. (1998) A Methodology of Calculating the Risk to People in Building Fires, Human Behaviour in Fire, Proc 1st Int Symp, ed. Shields,TJ, University of Ulster, p. 401- 410.

Appendix 1: EU leaflet



What to do when you are entering a tunnel

- **Listen to the radio** station indicated by the sign
- Switch on your **headlights.** Take off your **sunglasses**
- **Obey traffic lights** and **signs**
- **Keep** a safe **distance** from the vehicle in front
- **Do not overtake** if there is only one lane in each direction
- **Do not turn** or reverse. **Do not stop**, except in an emergency

What to do in the event of breakdown or accident

- Switch on your **warning lights**
- Try to **move your vehicle** to an **emergency lane** or **lay-by** or at least to the hard shoulder
- **Switch off the engine**
- **Leave your vehicle**
- If necessary and possible, give **first aid** to **injured people**
- **Call for help** from an emergency station

What to do in traffic congestion

- Switch on your **warning lights**
- **Keep your distance**, even if you are moving slowly or have stopped
- **Switch off your engine**, if the traffic has come to a halt
- **Listen to** messages on the **radio**
- **Follow the instructions** given by tunnel officials or **obey variable message signs**

What to do if your or another vehicle is on fire

- If your vehicle is on fire, if possible **drive out of the tunnel**
- If that is not possible, **pull over** to the side, **switch off the engine** and **leave the vehicle** immediately
- **Call for help** from an emergency station
- If you can, **put out the fire** using an **extinguisher** available in the tunnel
- If you can, **give first aid** to injured people
- **Go**, as soon as possible, to an **emergency exit**

Remember: Check fuel and turn on radio before entering a tunnel!

Remember: Fire and smoke can kill - save your life, not your car!

Appendix 2: Instructions for the TNO driving simulator study

Shortly you will receive the key for the simulator car. This key performs like a normal car key, which means you will use it to start the engine. The driving simulator functions like a normal car, meaning you can use the gas pedal, brake and steering wheel just like you normally would. Everything is in the same place as in an ordinary car: the warning lights, the headlights, heating, radio, safey belt, mirrors etc. The experimentator will show you everything more specifically ones you are seated in the car. The car has an automatic gear shift, so you do not need to shift gear. You can accelerate without shifting gear, the car does this automatically. This means that you don't have to use your left foot at all (normally you use this for shifting), just operate the gas and brake-pedal with your right foot, like you normally would.

Once you have started the engine you can start driving. Each drive will start at the entrance lane of a highway. You will enter the highway and just keep driving (there's no need to exit the highway) and drive as you normally would in real traffic.

We will ask you to verbalize everything you see, notice, think, and plan to do. The experimenter will monitor this through the intercom. It is very important for us that you will verbalize your thoughts: name were you are looking at, what you notice, why you act the way you do, etc. The more you say the better.

Every drive will be stopped automatically after which the next drive is started and you will be positioned again at the entrance lane of a highway. After each drive you will be asked to center the steering wheel and turn off the engine and restart it. The next drive will then begin.
At the end of the drives the experimenter will indicate that the experiment is finished and you will be asked to fill in a questionnaire. That concludes the experiment.

Thank you very much for your cooperation!

Appendix 3: Questionnaire for the TNO Driving simulator study (10 questions)

1) Describe in short what happened according to you in the last drive.

2) When did it occur to you what was going on?

3) What kind of information did you use to understand what was going on?

4) When did you decide to take action or, what refrained you from taking action?

5) Why did you do what you did?

6) Was there anything you were wondering about or was there information lacking?

7) Is there anything that you would have done differently in reality?

8) Have you ever witnessed or been involved in an incident or accident in a tunnel?

9) How do you normally experience driving through a tunnel (scary, not a problem at all, etc.)?

10) Is there anything else you would like to mention?

Appendix 4: Summary of verbal comments from the TNO driving simulator study

Condition 1:

Subject	beginning	operator: motor	smoke	operator: evacuate
1	traffic queue	-	something is not right, would have to get out and follow emergency route	-
2	busy, standing still, peak hour traffic	-	something going on, possible accident. Do not know what to do. I think I would go out	-
3	traffic queue or accident, keep distance, standing still, put radio on	-	something on fire, I see emergency exits and fire extinguishers, I will drive out backwards if others will do so. I would get out.	-
4	standing still: maybe an open bridge or an accident	-	there is a fire	-
5		-	there is a fire, do I drive out backwards?	-
6	have to keep distance, put on radio, maybe I will learn what is going on	-	Smoke, so probably a fire. I still see the entrance, so would walk in that direction	-
7	traffic queue	-	probably fire, walk backwards	-
8	keep distance	-	there is a problem, but do not see emergency services. Everyone remains seated. I would get out.	-
9	traffic queue, keep distance, uncomfortable to stand still in tunnel, can't drive over emergency lane (not present), can always get out via entrance	-	would get out	-
10	use radio to find out details, maybe accident	-	would walk towards entrance	-
11	traffic queue	-	accident, see no fire trucks. No phone with me to call 112, getting out is not wise, could always use emergency door on the left side	-
12	traffic queue	-	boiling motor of car, would like to drive backwards, danger is that everyone would do this	-

13	traffic queue	-	close window, get out of car and walk to tunnel exit	-
14	traffic queue	-	safety belt off in case there is something going on. I would leave the car	-
15	keep distance, traffic queue, turn on radio	-	get out of the car and see if I can help someone	-
16	traffic queue, turn on radio for traffic information	-	you can't see in front of you, so do not know what to do, get out and run?	-
17	keep distance, something going on in the tunnel	-	close window, best to stay in car, since there is no place to go, will not abandon my car, no police around	-
18	traffic queue,	-	boiling motor of car? close window, better to drive backwards, turn radio on	-
19	radio for traffic messages	-	leave car and walk in direction you came from	-
20	standing still, possible accident	-	car on fire? do not know what I would do, probably panic since there is no view	-

Condition 2:

Subject	beginning	operator: motor	smoke	operator: evacuate
21	traffic queue, maybe something happened, turn on radio		I'll stay in, I will go out, but maybe I will suffocate, rather stay in, will go out, but cannot see anything	-
22	busy, traffic queue, keep distance, turn on radio, traffic information, probably something happened at the end of tunnel, no panic, no emergency services		fire, leave car and lay on the ground, walk towards emergency exit, walk left and right to see where they are	-
23	traffic queue, radio for music		close window, tendency to stay inside, wait what others do, door open en walk towards the exit of the tunnel	-
24	peak hour,		maybe a car on fire? see if there	-

	standing still, probably an accident		are emergency exits, can't see any......	
25	-	-	gets out	-
26	radio already on, traffic queue, standing still, switch off engine		fire, I am getting out	-
27	radio already on		close window, get rid of safety belt....	-
28	traffic queue		get out of car and run	-
29	traffic queue, no traffic signalling		fire in engine, switch off engine. Think I would get out, but do not know what type of gas and can't see anything...	-
30	keep distance, switch off engine		car on fire? get out and go to emergency exit	-
31	radio already on, was traffic information about us? leaflet says to switch off engine, normally after 1 minute. normally after minutes I get out and see what is going on, if others get out I will also		see what happens, outside probably worse than in car, was expecting instruction, enough oxygen in car, will wait. Probably car on fire, how bad can it be?	-
32	traffic queue, turn on radio		get out	-
33	traffic queue, good visibility of emergency door, turn on radio		looks like fire, what do I do? get out and run to exit, away from smoke	-
34	keep distance, maybe collision?		car on fire? get out	-
35	traffic queue, turn on radio, undo safety belt		get out of car	-
36	-		close window, do I have to get out? What direction? see what happens, what radio freqency? I can get out but do not know where to go and where it is safe	-
37	radio alrady on, keep distance, switch off engine		close window, probably get out and go to emergency exit?	-
38	switch off engine		put car on the right side, should have kept more distance, would try	-

			to find tunnel exit	
39	there is something wrong, switch off engine		would undo safety belt and get out of car	-
40	traffic queue		no idea what to do, I think getting out	-

Condition 3:

Subject	beginning	operator: motor	smoke	operator: evacuate
43	radio already on. Standing still, change frequency	I will switch it off	close window, we have to get out. Get out.	(was already out)
44	traffic queue	switch off	we have to get out	(was already out)
45	-	switch off	close window	undo safey belt, door open
46	traffic queue	switch off	-	in principle I would have to get out and walk to emergency doors, that is what I would have to do
47	standing still, look for possible emergency doors	switch off, see of people in front of me do something	want to get out of cxar and flee to emergency doors	get out of car
48	peak hour traffic or accident	switch off	-	undo safey belt, door open
49	traffic queue, standing still	switch off engine	there is smoke, fire. Did read leflet but do not know what to do. I have to get out.	would get out
50	standing still, turn on radio	switch off	leave vehicle	(was already out)
51	busy traffic, keep distance. Standing still: switch off engine	(was already done)	want to het out and wlk away	I am getting out
52	traffic queue, standing still	switch off	something happened, windows are closed	I have to het out of car
53	radio already on, traffic queue, standing still	switch off,	close windows, turn on radio, what frequency?	get out
54	radio already on	turn radio off	I am getting out	gets out
55	standing still	switch off	does not look good	gets out

56	radio on for traffic queue information	switch off	gets out	(was already out)
57	keep distance, standing still	switch off	undo safey belt, gets out	(was already out)
58	peak hour, traffic queue, standing still, turn up volume of radio	switch off, switch off ventilation	accident, get out	(was already out)
59	radio already on, standing still	switch off	do not know what to do, will wait	will get out
60	radio already on	switch off engine plus radio, switch radio back on	-	undo safey belt and get out

Appendix 5: Interviewing the operator

Introduction

In the UPTUN deliverable 3.2, the COLFUN framework was described. This framework is used to describe the tasks and the mental load of operators in process control environments. This model was used in this task to
1) identify problems that can occur within the work of tunnel operators and
2) define solutions for these problems.

Because the model is quite extensive, a simplified version of it is presented in this document. The framework can be used to analyse existing data or acquire new data.
This document is aimed at part (1).
For this purpose, it contains a questionnaire and some guidelines for its use.

Method

Step 1: task identification

For task identification, an inventory is made of all operator tasks, classified in situation assessment and decision making and control. This concerns tasks during normal situations (e.g. a traffic jam) and incidents or accidents (e.g. a fire). Tasks can be listed like below (see also the main text of the deliverable, Chapter 7):

Situation assessment task	Decision making and control task
Tasks, especially relevant in normal tunnel operations: situation awareness and disturbance assessment. E.g. watching camera images, alarm handling, et cetera.	Tasks, especially relevant in incident situations: decision making, direction and control. E.g. speed limitation in tunnel, close barriers, call police.

Step 2: Inventory of bottlenecks

The results from the questionnaire can be used to make an inventory of bottlenecks in the operator task:
- Which task or combination of tasks can cause problems?
- Why do they cause problems?

Bottlenecks in the operators task design can be identified by using the cognitive load model.

Step 3: Definition of possible solutions

See the main text of this deliverable, in which this document was used to make an inventory of operator tasks and bottlenecks and solutions were defined, based on the results.

Analysing existing data

In retrospect, available data can be analysed following the method. At first, the data has to be filtered that is related to the tunnel operator. Secondly, from this data the operator tasks have to be identified as much as possible. Third, supported by the cognitive load model bottlenecks should be identified. When bottlenecks are already mentioned, it should become clear to what tasks these bottlenecks are related. Finally, solutions for the bottlenecks should be defined.

Operator interviews

The method can also support in making a questionnaire for the operator interviews. The questionnaire should cover items about the operator tasks during normal and incident situations. At the same time, it should cover items about

the cognitive load of the operator. It should facilitate the operator to uncover tasks / situations that are difficult to handle.
The questionnaire in below was developed according to the method. It is possible to send the questionnaire to the tunnel operators and ask them for a written reply. However, in order to get a good understanding of the operator and possible issues that are not on the list, we recommend using the questionnaire in a face-to-face interview.

Questionnaire

Control system

1. What means are available to inform you about the status in the tunnel?
    - ❑ Cameras
    - ❑ Speed detection system
    - ❑ CO sensors
    - ❑ Sight sensors
    - ❑ Temperature
    - ❑ Smoke detectors
    - ❑ Height detectors
    - ❑ Aid station sensors
    - ❑ Communication system in tunnel
    - ❑ Others: …..

2. What means are available to control the situation in the tunnel?
    - ❑ Electronic traffic signs
    - ❑ Intercom
    - ❑ Traffic lights
    - ❑ Barriers
    - ❑ Ventilators
    - ❑ Others: ….

3. When does the system produce alarms to notify certain events? Indicate if these alarms are presented visually, acoustically (sound) or both.

	Visual	Acoustic	Both
❑ The system does not produce any alarms			
Low traffic speed	❑	❑	❑
CO level too high	❑	❑	❑
Temperature too high	❑	❑	❑
Limited sight	❑	❑	❑
Vehicle too high	❑	❑	❑
Aid station in use	❑	❑	❑
Smoke in tunnel	❑	❑	❑
Others: ….	❑	❑	❑

4. What is the mean number of alarms (more or less) that is presented within an hour?
   ……

5. Are you satisfied with the alarms? (You’re allowed to tag more than one answer)
    - ❑ Yes
    - ❑ No, because there are too many alarms
    - ❑ No, because some alarms are not relevant

- ❑ No, because some alarms are missing
- ❑ No, because …

6. Do the cameras give you a good view on the situation inside the tunnel? (You’re allowed to tag more than one answer)
    - ❑ Yes
    - ❑ There are no cameras available
    - ❑ No, because the distance between cameras is too long
    - ❑ No, because the cameras don’t cover every spot in the tunnel
    - ❑ No, because the images are unclear
    - ❑ No, because takes a long time to find the camera that covers the right location
    - ❑ No, because …

7. When the cameras are not usable (e.g. when it is covered by a vehicle or in case of smoke), is there another way to get informed about the situation inside the tunnel?
    - ❑ No
    - ❑ Yes: ……

Incidents

8. What are the things that can happen in the tunnel which you have to be aware of? (You’re allowed to tag more than one answer)
    - ❑ Congestion
    - ❑ Poor sight
    - ❑ CO level too high
    - ❑ Vehicle that is too high
    - ❑ Tunnel system malfunctions (e.g. illumination, electronic signs, ventilators)
    - ❑ Load fallen off from truck
    - ❑ Broken car
    - ❑ Car against barrier
    - ❑ Collision
    - ❑ Fire
    - ❑ Others, …

9. Which of these things happen the most often?
    ……

10. How much time (more or less) does it take before you detect such an incident?
    ……

11. When this happens, do you immediately know what to do?
    - ❑ No, it takes some time to find out what to do
    - ❑ Yes, then I will do the following: ……

12. What incident you can think of do you consider as the most severe?
    ……

13. How much time (more or less) does it take before you detect such an incident?
    ……

14. What is the first thing you do when this happens?
……

15. What is your main task during these incidents?
……

16. Are there emergency plans for severe incidents?
    - ❑ Yes
    - ❑ No, go to question 19

17. If yes, do you know what procedures to follow? (You're allowed to tag more than one answer)
    - ❑ No
    - ❑ Yes, I know them by heart
    - ❑ Yes, they are on paper in the control room
    - ❑ Yes, they electronically available in my system
    - ❑ Yes, I have access to them in another way: ……

18. Do the emergency plans work properly during these incidents?
    - ❑ Yes, they do
    - ❑ I don't know, I never experienced such an incident
    - ❑ No, because …

19. How much time does it take for the emergency services to arrive at the tunnel from the moment you warn them?
……

20. In the meantime, what tasks do you have to perform? (You're allowed to tag more than one answer)
    - ❑ Monitoring the tunnel
    - ❑ Evacuate tunnel users
    - ❑ Communicate with tunnel users
    - ❑ Communicate with others (e.g. superiors, authorities, emergency services)
    - ❑ Other tasks: ……

21. Do you have to perform these tasks alone?
    - ❑ Yes
    - ❑ No, in such situations I get assistance from …

22. Are you able to perform these tasks properly? (You're allowed to tag more than one answer)
    - ❑ Yes
    - ❑ No, because I have to do too many things at the same time
    - ❑ No, because it is not clear what actions to take
    - ❑ No, because I get unclear or conflicting instructions
    - ❑ No, because the incidents do not occur very often, so I don't know exactly what to do
    - ❑ No, because the system is too difficult to operate
    - ❑ No, because …
    - ❑ …….

23. Do you know what procedures to follow specifically with respect to the rescue services?
    - ❑ No
    - ❑ Yes, I know the procedures
    - ❑ Yes, they are on paper in the control room
    - ❑ Yes, they are electronically available in my system

- ❑ Yes, I have access to them in another way: …..

24. If yes: do you know if these procedures have been agreed upon between the tunnel owner and the rescue services?
    - ❑ Yes, I know they have.
    - ❑ Yes, I know they have not.
    - ❑ No, I do not know.

25. What do you do after the situation has returned to normal? (You are allowed to tag more than one answer)
    - ❑ Write an incident report
    - ❑ Inform a superior about what has happened
    - ❑ Register the incident in a computer system
    - ❑ Other tasks:….

Shifts

26. Do you work in shifts?
    - ❑ Yes
    - ❑ No

27. If yes, what are the working hours of the different shifts?

    Shift 1:

    Shift 2:

    Shift 3:

    Shift 4:

28. What shift do you prefer the most?
    ……

29. What shift do you prefer the least?
    ……

30. How many breaks do you have during your work?
    ……

31. Who is watching the tunnel during your break?
    ……

32. When your shift is over, do you have to report to your colleague of the next shift?
    ……

33. If yes, how does this take place?
    ……

Training

34. Did you get any training before you started to work as a tunnel operator? (You're allowed to tag more than one answer)
    - ❑ No

- ❑ Yes, I got training ‘on the job’ from an experienced tunnel operator
- ❑ Yes, I did a training course of … weeks
- ❑ Yes, I had another form of training: ……

35. Do you have any training courses to refresh your skills and knowledge?
    - ❑ No
    - ❑ Yes, every … months

36. Are there training sessions with the emergency services to learn what to do during severe incidents (e.g. a fire in the tunnel)?
    - ❑ No
    - ❑ Yes, every … months

37. If yes, do you consider these training sessions as useful?
    - ❑ Yes
    - ❑ No, because …

Appendix 6: Ergonomics background

Man and machine

According to Taylor and Garvey (1959), human factors (ergonomics) are concerned with ‘fitting the job to the man’ rather than the other way around. The environment should be designed with the operator in mind, rather than operators being forced to adapt to the system's demands. This is an argument that is gradually becoming accepted in most modern systems and therefore also in traffic. If the environment is conceived and constructed well but important facets of the human operator and behaviour are not considered, the system will not operate at maximum safety and efficiency and errors will result. Such effects will occur no matter how carefully the individual has been selected for the task or how well he has been prepared to accomplish the tasks.

Human factors is a multidisciplinary field of study which comprises a combination of physiology, anatomy and medicine as one branch, psychology and experimental psychology as another, and physics and engineering as a third. From these disciplines and sub-disciplines we take and integrate information to maximize driver's safety, efficiency and performance reliability.

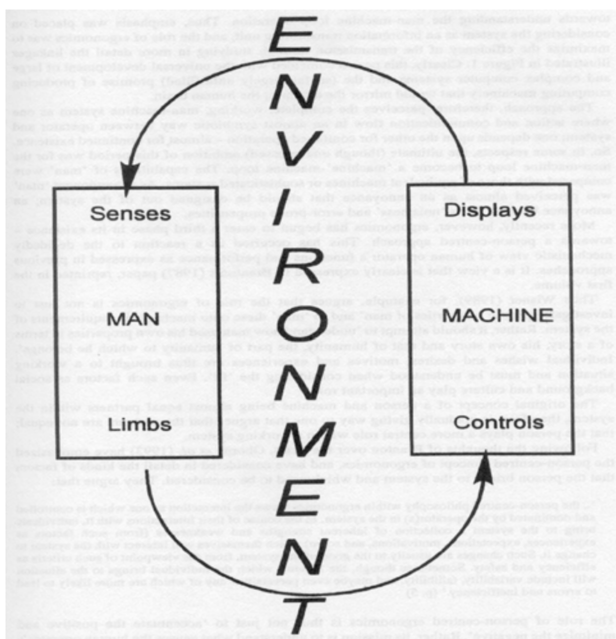


Figure A6-1: The traditional man-machine system (Oborne, 1995).

Traditional ergonomics generally accept that the basic unit of the interaction is the “man-machine loop”, which has two prime components: man and machine that are linked by information loops. Information from machines in the environment is passed to the operator through the machine's displays and the operator's perceptual system. Controlling information has the opposite direction and is passed via the operator's limb to the machine controls. Around it is the environment that can affect the nature and efficiency of any information loop (Oborne, 1995).

The system is considered an information transmitting unit, and the role of ergonomics is to maximize the efficiency of the transmission through studying the linkages in more detail, as illustrated in Figure 87. The man-machine system is perceived as a complete system with action and communication flow between operator and system. More recently ergonomics have begun to enter a third phase in their existence – toward a more person-centred approach. This has occurred as a reaction to the mechanistic view of human operator's functions and performance as expressed in previous approaches. The role of ergonomics is not just to investigate specific “properties of man” and to “map” these onto mechanistic requirements of the system. It should attempt to understand how someone uses his own properties in terms of a story, his own and of humanity, the part of humanity to which he belongs. In considering the "fit" individual wishes and desires, motives and experiences must be understood. Even such factors as background and culture play an important role. The person-centred ergonomics have the mission to understand what causes the human operator's positive and negative features to arise and to design the system to accommodate them.

Ergonomics play an important role in different areas of road tunnel safety. These areas include traffic, communication, tunnel operations and rescue. Some experts implicitly assume perfect human behaviour in a well constructed and equipped tunnel. But it is a matter of fact that in incident cases a lot of people do not react adequately to the situations, mostly because they lack knowledge on how to behave adequately.

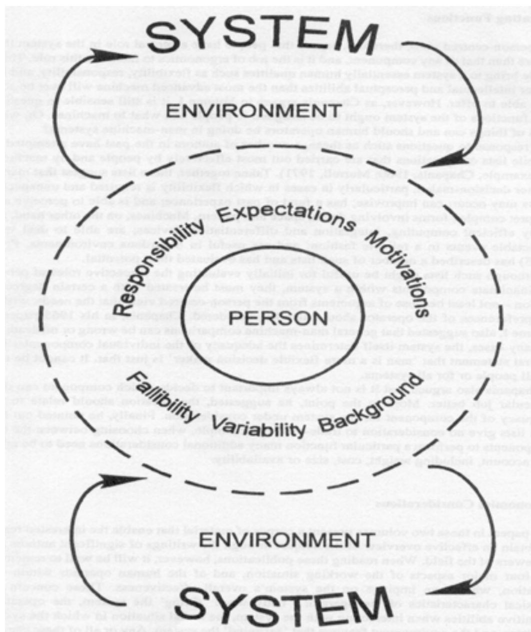


Figure A6-2: The person-centred approach (Oborne, 1995).

In the person-centred approach people have a central role in the system and the job of ergonomics is to facilitate this role. People bring to a system human qualities such as flexibility, responsibility, and intellectual and perceptual abilities. A number of authors in the past have attempted to compile lists of operations that are carried out most effectively by people and by machines. Taken together, these lists suggest that man is a better decision-maker, particularly in cases in which flexibility is required and unexpected events may occur. Man can improvise, has a fund of past experience, and is able to perceive and interpret complex forms involving depth, space and pattern. On the other hand machines are highly efficient in computing, integration and differentiation devices, are able to deal with predictable events in a reliable fashion, and are useful in hazardous environments.

Table A6-1: The abbreviated list of some of the relative advantages and disadvantages of men and machines (from Chapanis, 1960 and Oborne, 1995).

MEN	MACHINES
Able to handle low probability alternatives, i.e. unexpected events.	Difficult to program. Difficult to anticipate all possible events and so virtually impossible to program for all such contingencies.
Able to perceive, i.e. to make use of spatial and	Zero, or very limited, ability to perceive.

temporal redundancies and so to organize many small bits of information into meaningful and related 'wholes'.	'Organization' has to be elaborately programmed, which is difficult to do because of the many alternative ways organization can be formed from elements.
Possess alternative modes of operation. Can accomplish same or similar results by alternative means if primary means fail, or are damaged.	Alternative modes of operation limited. May break down completely when partial injury or damage occurs. Not able to regenerate or heal.
Limited channel capacity, i.e. there is a maximum amount of information that can be handled per unit time, and this is small.	Channel capacity can be made almost as large as desired.
Performance subject to decrement over fairly short time periods because of fatigue, boredom, and distraction.	Behaviour decrements only over relatively long periods of time.
Comparatively slow and poor computers.	Excellent and very rapid computers.
Flexible: can change programming easily and frequently. Very large number of programs possible.	Relatively inflexible. Flexibility in kind and number of programs can be achieved only at a great price.

But such lists must be treated with a certain degree of caution. In many cases the system itself determines the adequacy of the individual components. There are four major aspects of the working situation and human operator within that situation: psychical features, cognitive components, social circumstances, and environmental elements. These concern the physical characteristics of the operator's body when 'fitting' the system, the operator's cognitive abilities when interacting with the system, the social situation in which the system operates, and the environment features that surround the system.

At a physical level information about the body size and dimensions and the extent to which limbs can move and operate particular parts of the system is considered. Operating any part of a system requires work, which takes the form of physical/muscular work. As a consequence of inadequate considerations of the operator's physical abilities, muscular fatigue can soon occur. Such fatigue can act as an inhibitor to effective work and in the long term disabilities and industrial injuries can occur. The communication link between the operator's action and the machine's display is carried out through perceptual, judgmental, linguistic and conceptual cognitive levels. Whatever tasks are being done, the activity will generally be performed within some kind of social context. Other people form part of the working system and interaction with operator. Through elements of the environment communication and working behaviour occur, and through them the effective physical, cognitive and social links take place. All these features act in a synergistic manner. Working system depend on the person, the task, the environment, and the system itself.

Crisis management

Tunnels are complicated systems that are also inherently including a possibility of errors and accidents (Perrow, 1976). In spite of this uncertainty the system must be prepared for emergency cases. The types of error, malfunctions and accident and their probability must be known on the basis of research and previous experience. This information is necessary for the preparation of emergency measures and organization of the work of the staff dealing with emergency. In addition the rules and instruction about the safe behaviour in such emergency must me transmitted to the road users. This is especially important in fire situation, where the natural human reactions (fear, inaction) must be counteracted. Besides the knowledge necessary for crisis management a system of communication between tunnel users and operator must be developed that enables on line contacts and prompt reporting of events.

Accidents in tunnels may convert to a disaster, even to a catastrophe, but in any case they are a crisis and demand crisis management. Incident commanders in such cases are faced with extremely difficult decisions, characterized by ambiguous and conflicting information, shifting goals, time pressure, dynamic conditions, complex operational team structures, and poor communication and circumstances where every available course of action carry significant risk (Flin, 1996).

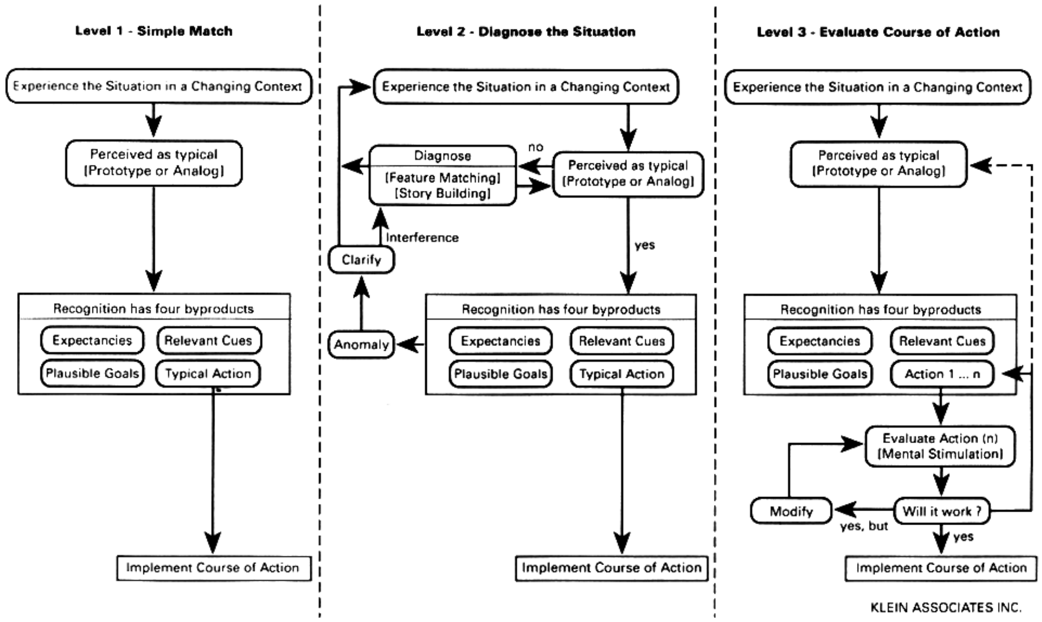


Figure A6-3: Recognition-Primed Decision model (Klein, 1995)

We shall not discuss here characteristics of incident commanders and teams, or of the stresses they are exposed to, but only some characteristics of decision they should make. Since mid-1980s the previous traditional normative decision-making models were exchanged with so called naturalistic decision making models. Klein (1995; 1998) proposed so called recognition-primed decision making model (Figure 88). The model has three basic forms. In the simplest version (Level 1) the decision maker recognizes the type of situation as typical, knows the appropriate response and implements it. By recognizing a situation as typical he also recognize a course of action likely to succeed. When the situation is more complex and/or decision maker cannot so easily classify the type of problem faced, then (Level 2) there may be a more pronounced situation assessment phase. This can involve a simple feature match, where the decision maker thinks of several interpretations of the situation and uses key features to determine which interpretation provides the best match with the available cues. Alternatively, the decision maker may have to combine these features to construct a plausible explanation for the situation. Where the appropriate response is unambiguously associated with the situation assessment, it is implemented. In cases where the decision maker is less sure of the option, then the model on Level 3 indicates that before an action is implemented there is a brief mental evaluation to check whether it is likely to be any problems (mental simulation). This approach also changes the nature of training, emphasising the knowledge of relevant cues and adequate actions.

Appendix 7: Additional tables

The tables in this appendix were used to specify recommendations in Chapter 7 of the main text. The first table shows the analysis of the bottlenecks identified after analysing the operator tasks. Solutions are listed for each of the bottlenecks. The second table shows roughly the same information, only rearranged into categories that represent the general methods for improving operator performance.

Bottlenecks and possible solutions

#	Bottleneck	Bottleneck type	Generic solution	Improvement method	#	Solution
01	During long periods of normal operation, vigilance may be threatened. This is especially critical during the night (3-6 a.m.), when tunnel users are also less alert.	Cognitive underload risk	Increase cognitive task load	Training and exercise	04	Provide means and time to switch between the monitoring task and studying new procedures or other activities.
				Personnel and organisation	12	Make sure there are enough operators on duty so no one has to monitor the tunnel(s) for too long a time and other tasks may be executed.
				Control room and interface design	18	Provide the necessary means to keep the operator alert. Example: temperature in control room; force him (using alarms) to take certain actions.
02	Bad or absent incident handling procedures; especially unclear allocation of responsibilities and authority to personnel.	Rule-based mistake: no rule or bad rule	Make rule or change rule	Training and exercise	11	Evaluate exercises to reveal flaws or inefficiency in operation procedures.
				Task support	16	Provide standard emergency plans; coordinate these with rescue services and make sure these plans are written, verified, well-known, used and revised if necessary.
				Control room and interface design	27	Provide tools to support disturbance handling and incident procedures. Tools should correspond with written procedures.
03	Insufficient skills due to lack of practice exercises, especially with the rescue services.	Knowledge-based mistake	Educate or change personnel	Training and exercise	06	Test operators periodically to make sure that training and exercise plans are executed.
04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.	Suboptimal cognitive load	Optimize cognitive task load	Training and exercise	05	Use operation procedures in training and exercise: activities can move from knowledge-based to rule-based or from rule-based to skill-based.
					04	Provide means and time to switch between the monitoring task and studying new procedures or other activities.
				Personnel and organisation	12	Make sure there are enough operators on duty so no one has to monitor the tunnel(s) for too long a time and other tasks may be executed.
					13	Make sure there are enough operators present (and standing by) to, if necessary, take over certain tasks.
				Control room and interface design	18	Provide the necessary means to keep the operator alert. Example: temperature in control room; force him (using alarms) to take certain actions.
					26	Use loud alarms for important detection signals.
05	Overdue, incorrect or incomplete detection of incident due to	No error but lack of tools or wrong	Provide adequate tools	Control room and interface design	19	Provide an interface sufficiently effective to alert the operator if

#	Bottleneck	Bottleneck type	Generic solution	Improvement method	#	Solution
	combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.	tools				anything is wrong, if possible not only a visual signal on screen, but also, for example, a sound signal.
06	Operator is panic-stricken and does not respond (adequately) to incident.	Unintended action	No generic solution applicable	Recruitment	01	Apply the ability to handle stress as a selection criterium.
07	Starting from the escalation stage, many different decisions and actions are required in a short time.	Cognitive overload risk	Lower cognitive task load	Training and exercise	05	Use operation procedures in training and exercise: activities can move from knowledge-based to rule-based or from rule-based to skill-based.
				Personnel and organisation	13	Make sure there are enough operators present (and standing by) to, if necessary, take over certain tasks.
				Control room and interface design	21	Equip the work place so as to make sure that a minimum of actions (and time) is required to execute decisions.
					20	Apply group commands for sets of actions that are the same for all serious incidents.
					27	Provide tools to support disturbance handling and incident procedures. Tools should correspond with written procedures.
08	Too many incoming signals, not all of which are relevant at this time.	Cognitive overload risk	Lower cognitive task load	Control room and interface design	23	Make it possible for the operator to switch off alarms during an incident.
					22	Make it possible to suppress all alarms that are irrelevant during an incident in progress.
09	Insufficient means to communicate with other operators, rescue services or tunnel users.	No error but lack of tools or wrong tools	Provide adequate tools	Control room and interface design	25	Make sure that means of communication for operators and rescue services are reliable and accessible to all parties concerned.
					24	Apply tools to address, guide and communicate with tunnel users.
10	Insufficient skills and / or knowledge to communicate with other operators, rescue services or tunnel users.	Knowledge-based mistake	Educate or change personnel	Training and exercise	07	Train communication procedures. If necessary, provide a language course.
				Personnel and organisation	14	If language is an issue: assemble control room crew from both language regions.
11	Operator does not succeed in convincing tunnel users to escape.	Rule-based mistake: misapplication	Educate or change personnel	Recruitment	02	Apply the presence of communication skills as a selection criterium. Staff should be able to communicate with tunnel users in a decisive and calm manner.
				Training and exercise	08	Train and exercise communication skills.
12	Operator does not indicate right way for fleeing or does this too late.	Knowledge-based mistake	Educate or change personnel	Training and exercise	09	Include knowledge of tunnel lay-out and tunnel equipment in procedures, training and exercise.
13	Absence of or insufficient coordinated procedures between operators and rescue services.	Rule-based mistake: no rule or bad rule	Make rule or change rule	Task support	16	Provide standard emergency plans; coordinate these with rescue services and make sure these plans are written, verified, well-known, used and revised if necessary.
				Control room and interface design	27	Provide tools to support disturbance handling and incident procedures. Tools should correspond with written procedures.
14	Absence of adequate incident evaluating and registration procedures.	Rule-based mistake: no rule or bad rule	Make rule or change rule	Task support	17	Provide an adequate, low-threshold and well-known procedure for incident evaluation and registration.
15	Mistake in incident is not evaluated or registered due to fear for career consequences.	Violation	Educate, change organisation or personnel	Personnel and organisation	15	Make sure the company culture provides a 'safe' environment for learning from mistakes.

#	Bottleneck	Bottleneck type	Generic solution	Improvement method	#	Solution
16	Incident is not evaluated or registered although adequate procedure is available and known.	Violation	Educate, change organisation or personnel	Recruitment	03	Apply attitude towards improving one's own task as a selection criterium.
				Training and exercise	10	Evaluate exercises and training sessions for improvements in procedures and actions, to convince personnel of the need for experience-based improvement.

Solutions by improvement method

Improvement method	#	Solution	Tools	#	Bottleneck
Recruitment	01	Apply the ability to handle stress as a selection criterium.		06	Operator is panic-stricken and does not respond (adequately) to incident.
	02	Apply the presence of communication skills as a selection criterium. Staff should be able to communicate with tunnel users in a decisive and calm manner.		11	Operator does not succeed in convincing tunnel users to escape.
	03	Apply attitude towards improving one's own task as a selection criterium.		16	Incident is not evaluated or registered although adequate procedure is available and known.
Training and exercise	04	Provide means and time to switch between the monitoring task and studying new procedures or other activities.	Duty rotation; training techniques.	01	During long periods of normal operation, vigilance may be threatened. This is especially critical during the night (3-6 a.m.), when tunnel users are also less alert.
				04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
	05	Use operation procedures in training and exercise: activities can move from knowledge-based to rule-based or from rule-based to skill-based.	Training techniques.	04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
				07	Starting from the escalation stage, many different decisions and actions are required in a short time.
	06	Test operators periodically to make sure that training and exercise plans are executed.	Training techniques.	03	Insufficient skills due to lack of practice exercises, especially with the rescue services.
	07	Train communication procedures. If necessary, provide a language course.	Standard calamity plan; training techniques.	10	Insufficient skills and / or knowledge to communicate with other operators, rescue services or tunnel users.
	08	Train and exercise communication skills.	Training techniques.	11	Operator does not succeed in convincing tunnel users to escape.
	09	Include knowledge of tunnel lay-out and tunnel equipment in procedures, training and exercise.	Simulations.	12	Operator does not indicate right way for fleeing or does this too late.
	10	Evaluate exercises and training sessions for improvements in procedures and actions, to convince personnel of the need for experience-based improvement.	Training techniques.	16	Incident is not evaluated or registered although adequate procedure is available and known.
	11	Evaluate exercises to reveal flaws or inefficiency in operation procedures.	Training techniques.	02	Bad or absent incident handling procedures; especially unclear allocation of responsibilities and authority to personnel.
Personnel and organisation	12	Make sure there are enough operators on duty so no one has to monitor the tunnel(s) for too long a time and other tasks may be executed.		01	During long periods of normal operation, vigilance may be threatened. This is especially critical during the night (3-6 a.m.), when tunnel users are also less alert.
				04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of

Improvement method	#	Solution	Tools	#	Bottleneck
					risk factors in tunnel.
Personnel and organisation	13	Make sure there are enough operators present (and standing by) to, if necessary, take over certain tasks.		04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
				07	Starting from the escalation stage, many different decisions and actions are required in a short time.
	14	If language is an issue: assemble control room crew from both language regions.		10	Insufficient skills and / or knowledge to communicate with other operators, rescue services or tunnel users.
	15	Make sure the company culture provides a 'safe' environment for learning from mistakes.		15	Mistake in incident is not evaluated or registered due to fear for career consequences.
Task support	16	Provide standard emergency plans; coordinate these with rescue services and make sure these plans are written, verified, well-known, used and revised if necessary.	Standard calamity plan.	02	Bad or absent incident handling procedures; especially unclear allocation of responsibilities and authority to personnel.
				13	Absence of or insufficient coordinated procedures between operators and rescue services.
	17	Provide an adequate, low-threshold and well-known procedure for incident evaluation and registration.		14	Absence of adequate incident evaluating and registration procedures.
Control room and interface design	18	Provide the necessary means to keep the operator alert. Example: temperature in control room; force him (using alarms) to take certain actions.	Simulations; intelligent user interface.	01	During long periods of normal operation, vigilance may be threatened. This is especially critical during the night (3-6 a.m.), when tunnel users are also less alert.
				04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
	19	Provide an interface sufficiently effective to alert the operator if anything is wrong, if possible not only a visual signal on screen, but also, for example, a sound signal.	Intelligent user interface.	05	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
	20	Apply group commands for sets of actions that are the same for all serious incidents.	Group commands, such as calamity button.	07	Starting from the escalation stage, many different decisions and actions are required in a short time.
	21	Equip the work place so as to make sure that a minimum of actions (and time) is required to execute decisions.	Intelligent user interface.	07	Starting from the escalation stage, many different decisions and actions are required in a short time.
	22	Make it possible to suppress all alarms that are irrelevant during an incident in progress.	Calamity button.	08	Too many incoming signals, not all of which are relevant at this time.
	23	Make it possible for the operator to switch off alarms during an incident.	Intelligent user interface.	08	Too many incoming signals, not all of which are relevant at this time.
	24	Apply tools to address, guide and communicate with tunnel users.	Sound beacons, pre-recorded announcements.	09	Insufficient means to communicate with other operators, rescue services or tunnel users.
	25	Make sure that means of communication for operators and rescue services are reliable and accessible to all parties concerned.	Radio.	09	Insufficient means to communicate with other operators, rescue services or tunnel users.
	26	Use loud alarms for important detection signals.		04	Overdue, incorrect or incomplete detection of incident due to combination of suboptimal cognitive load and suboptimal detection of risk factors in tunnel.
	27	Provide tools to support disturbance handling and incident procedures. Tools should correspond with written procedures.	Decision support software.	02	Bad or absent incident handling procedures; especially unclear allocation of responsibilities and authority to personnel.
				07	Starting from the escalation stage, many different decisions and actions are required in a short time.
				13	Absence of or insufficient coordinated procedures between operators and rescue services.

Appendix 8: Tools and techniques

This appendix lists several examples of tools and techniques, which may be used to contribute to improving the operator's performance. The tools and techniques mentioned in this appendix are not the only possible means of support for the operator; maybe even better tools are available to a tunnel manager. Depending on local circumstances and the state of the art at the time, tunnel management organisations choose the most effective or efficient tools for reaching their goals.

Scenario analysis

Analysing a limited number of scenarios for incidents or accidents in tunnels may assist the process of improving operator performance in the following ways:

- It can be used to analyse the operator's tasks and give an insight into cognitive task load (underload and overload threats). In order to do this, the operator's tasks during an incident have to be identified and the time required to perform each of these tasks has to be known. In addition, one has to establish criteria: for example, what is the maximum time between detection of a fire and a fully operational escape route? If the time needed to prepare the escape route is longer than this, the need for improvement is obvious.
- Scenario analysis can also be used to select the most effective (efficient) strategy to improve operator performance.
- Finally, scenario analysis can be used to specify certain improvement measures. For example, incident management procedures can be written for several scenario types. Also, scenario analysis may help decide which commands can be clustered in a group. Training and exercise as well as training tools can also be based on scenarios.

Depending on the goal of a scenario analysis, the method and level of detail may vary. However, by comparing different types of scenario analysis a common model can be extracted (COB/RWS Centre for tunnel safety, 2004):

1) Start by recruiting specialists from all fields of expertise that you need (operations in emergency services, tunnel operation, analysis specialist). Form a scenario analysis team.
2) Establish goals and criteria for your analysis: when is a strategy effective? Or: what are the minimum and maximum levels for cognitive task load?
3) Describe the tunnel, safety measures present, rescue service data (such as time until arrival of fire rescue vehicles at the incident site).
4) Choose relevant incident scenarios, of different types and different scales. Ranging from a broken down vehicle via a small and a large fire to an explosion. Which scenarios are relevant to your situation, may depend upon your analysis goals and on the local situation. Describe the circumstances for your scenarios: day time or night time, rush hour? Heavy or light traffic? How many heavy goods vehicles? Busloads of elderly people? Shift switch for the operating crew? In some cases, it may be useful to include one or more scenarios taking place while maintenance work is in progress.
5) Analyse the scenarios.
   First, from the start of an incident scenario until all is again normal, choose time steps.
   At each of these steps, establish the situation in the tunnel and in the control centre (make "photographs"). How many vehicles are trapped in the tunnel? Has traffic at each of the tunnel entrances been stopped? How many people are present in the tunnel? Is anyone in need of rescue? Are escape routes ready for evacuation? Are people present in escape passages? What is the operator doing? What are rescue services doing? Et cetera. Drawing schematic pictures may be helpful here.
   All photographs together make an album describing the entire scenario.
   This is done for each of the chosen scenarios.
6) At this point, the results of the analysis can be compared to the goals and criteria established at the beginning. If goals are not reached, (additional) improvement measures have to be taken.

These steps can thus be schematically represented:

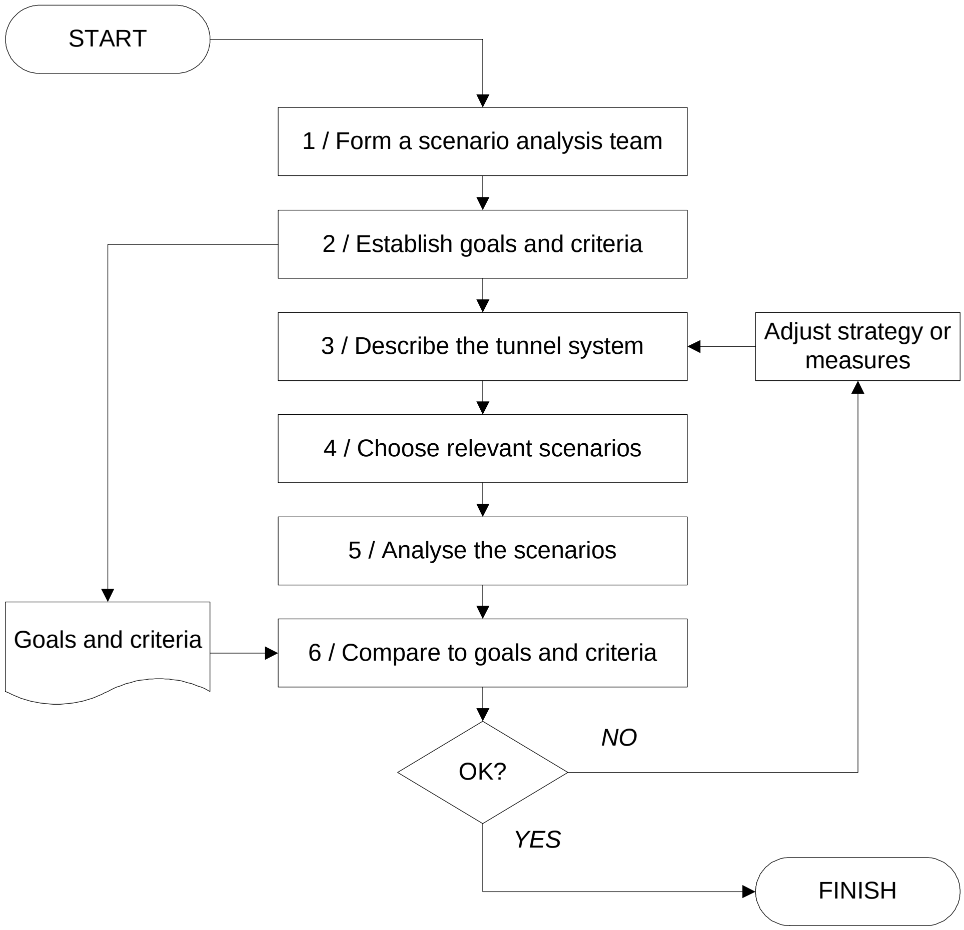


Figure A8-1: Model for scenario analysis

Dutch Standard Calamity Plan for road tunnels

In the Netherlands, several plans and instructions are generated for road tunnels. These plans deal with aspects such as traffic management and maintenance standards.
One of the plans is the so-called calamity plan, which describes the actions that have to be taken by the tunnel operator and the emergency services for several scenarios. The plan is written by the tunnel owner in cooperation with the emergency services to make sure that the efforts of the different parties involved are coordinated.

A standard Calamity Plan for road tunnels (RWS Centre for tunnel safety, 2002) has been generated in a coordinated effort by rescue services, the Ministry of Transport, Public Works and Water Management, the Ministry of the Interior, the large municipalities and the provinces. An English version is not (yet) available, but it contains the following information:

- General section:
    - Organisation and responsibilities in case of incidents
    - Geographical location for which the plan is applicable
    - Status of the plan in relation to other plans and documents
    - When and by whom is the plan put into action and how are personnel instructed and trained to use the plan?
- Task description for tunnel operator
    - What protocols are applicable

- How to act in several types of scenarios: situation assessment criteria and tasks
- Coordination and communication with rescue services and other parties involved
    - When and how to inform rescue services
    - Checklist of data needed for rescue services
    - General approach by rescue services
    - Where to place rescue vehicles in or outside of the tunnel
    - Who is in command of the rescue operation
    - Phone numbers of all relevant parties
    - How to handle contacts with others (general public, media etc.)
    - When and how to restore normal operation of tunnel
    - Incident evaluation checklist
- Appendices
    - Description of the tunnel and its equipment
    - Maps and plans of the surroundings, containing escape routes for tunnel users and approach routes for rescue services
    - Description of scenarios
    - Description of calamity organisation
    - Protocols
    - Exercise and training programmes
    - Background information on rescue and self rescue

Writers of calamity plans should be informed how to use the standard plan (written instruction).

At the moment, a standard safety management system for Dutch road tunnels is being developed in which this standard calamity plan will be included, along with requirements of procedures for traffic management, incident management, maintenance management (availability and reliability of installations) and personnel (predominantly aimed at recruitment, training and exercise).

French Disaster Management System (DMS)

An example of a disaster management system (DMS) is described in this section. Such a DMS ensures that everything is put in place for facilitating the coordination. This example has been defined with the INERIS experience of emergency planning within high hazard plants. The lessons learned from tunnel accidents have been integrated in the example.

In case of disasters - exactly as for organisations which pursue production goals - people interact in a coordinated way, following common objectives.

In emergency intervention, these objectives can be defined as follows:

Table A8-1: Nine "common objectives" for disaster responses, as defined by the UK Government (Home Office, 1997)

Common objectives
1. To save life.
2. To prevent the escalation of disaster.
3. To relieve suffering.
4. To safeguard the environment.
5. To protect property.
6. To facilitate criminal investigation and judicial, public, technical, or other inquiries.
7. To inform public.
8. To promote self-help and recovery.

9. To restore normality as soon as possible.

When people interact with common objectives, they need frames, rules, to coordinate their various and interdependent activities. In the case of an emergency response, a disaster management systems (DMS) must therefore provide the support for doing so.

A disaster management system should be included in safety management systems, for which the emergency preparedness is one issue among others. This is an example of a safety management system, from the SEVESO II directive, which specifies the activities to be implemented in a high hazard installation:

- Organisation and personnel
- Identification and evaluation of major-accident hazards
- Operational control
- Management of change
- Planning for emergencies
- Monitoring performance
- Audit and review

A disaster management system could be described as the coordination of the related activities -through standardisation and plans - ensuring the most appropriate planning and response in emergency situations, in order to fulfil the goals defined in Table A8-1.

Such a system requires to plan and to make formal:

- Potential accidental scenarios,
- Measures to be taken to reach the objectives of Table A8-1,
- Individuals to be involved in the measures taken,
- How/who gives the alert to whom,
- What equipment is required for mitigating accidental scenarios,
- What information is needed for the different potential individuals,
- The training/exercises required for individuals to implement measures,
- Lessons learnt from exercises to improve plans,
- The activities to be audited for ensuring the maintenance of operational readiness and areas to be improved.

We suggest to go through these different activities and comment on them. Many of these activities speak for themselves. This representation can be used as a frame for building a disaster management system. This frame is the result of a mix between safety management system principles and emergency preparedness knowledge at INERIS. Some practical lessons learnt, based on the NEDIES project, are included in this example of disaster management system activities.

NEDIES (Natural and Environmental Disaster Information Exchange System) was a project conducted at Ispra by the Institute for Systems, Informatics and Safety of the EC Joint Research Centre (JRC), in order to support European States and organisations to prevent and prepare for natural and environmental disasters and to manage their consequences.

The project has produced a report on lessons learnt from recent tunnel accidents.

Lessons learnt from some of the most important tunnel accidents, recently occurred in Europe : the Mont Blanc Tunnel fire (1999, 39 fatalities), two tunnel disasters occurred in Austria (Tauer tunnel accidents, 1999, 12 fatalities and Pfänder Tunnel accident, 1995, 3 fatalities). It also presents the lessons learnt from less tragic accidents but nevertheless full of lessons to be implemented.

Identify potential accident scenarios

The scenario identification that will serve as reference for planning intervention and identify what kind of equipment and number of people needed must be the result of risk analysis. According to the different size, traffic capacities and safety engineering features of the tunnel, different risks are considered probable.

Scenarios can be extracted from the risk analysis of the tunnel, or if not performed then a risk analysis must determine what kind of risks must be prevented.
The risk analysis phase must serve as well defining the minimal operation conditions.

The minimal operation conditions correspond to a "threshold" below which the safety of the users cannot be guaranteed any more. This can be the case is in the event of failure of equipment, because the compensatory measures do not make it possible to face the degraded operating mode any more, that is to say in case of traffic event, because the restrictions of circulation do not make it possible any more to face the risks of major disturbances. The minimal operation conditions indicate the minimal state of availability of the safety arrangements below which the tunnel must be closed with circulation. These minimal conditions must be defined by family of equipment and type of traffic event; they must be put in correspondences with the nominal operation conditions and the levels of degraded operation.

Identify measures to be taken to reach objectives (Table A8-1)

Here are the information from the NEDIES project that are relevant according to the objectives of a disaster management system:

1. To save life.
2. To prevent the escalation of disaster.
3. To relieve suffering.
4. To safeguard the environment.
5. To protect property.

- The best practical conditions of communication between the rescue organisations and the tunnel operator (alerting and further communication) must be ensured.
- It is crucial that the Service Tunnel area at the site of any incident is effectively managed. Failure to do so inevitably leads to delay and confusion. It is important that each service operating within a tunnel is aware of and adopts the principles agreed.
- The deployment of rescue teams greatly assists in the evacuation and first aid treatment of the passenger and crew and if this is not the case, and oxygen resuscitation/therapy equipment and trained personnel are not promptly available, the injuries to be sustained may increase seriously.
- The best practical conditions for rescue services to access to the fire place and have the physical and technical capacities to respond must be available.
- The general principles for the closing of the tunnel must be specified for a threshold of minimal operating conditions that are not respected any more. It must in particular define and justify the conditions of immediate closing by distinguishing the cases of technical damages :
    - Devices of civil engineering (impossible access, etc.)
    - Safety devices (reduced capacity of smoke clearing, reduced capacity of ventilation, quality of the air, visibility, power supply normal and/or help, reduced capacity of pumping, etc.)
    - Dynamic equipment (unavailable network of urgent call, unavailable system of remote monitoring, etc).

6. To facilitate criminal investigation and judicial, public, technical, or other inquiries.
7. To inform public.
8. To promote self-help and recovery.

- Effective coordination will allow operations at the incident site to continue safely and without interruption. Each incident site must be treated as a "scene of the crime" and preserved as such. It must be recognised that within these restricted areas there may be specific hazards. The demarcation and control of the inner cordon will be a matter for commanders to take into account according to the circumstances of the incident.
- Only authorised personnel, i.e. those having an accepted function, should be allowed within the inner cordon. The entry and exit of all persons and emergency service personnel must be logged in accordance with service procedures. Authority for access to the incident site for other than necessary emergency services must be sought from the Control Point. Records should be kept for evidential purposes.

Identify individuals to be involved in the measures taken,

In a first place, the operating services, for which must be specified:

- Their missions,
- a list of the human and material means available,
- a description of the composition of the teams and the materials available,
- an identification by which means it can be alerted,
- an identification of the methods of interventions.

The other individuals are the external actors:

- The police force,
- the firemen,
- services of management of the whole itinerary on which the tunnel is established,
- break-down mechanics, electrical supplier,
- local authorities,
- local rescue services,
- medical emergency services ,
- external Command Point.

For each one of these actors, their missions should be specified, as well as a list of the human and technical means, to indicate by which means they can be alerted (next activities). It must also clarify their interventions methods.

Among the things pointed out from experience, concerning the identification of relevant individuals, here are important things to be considered:

- A team responsible for press and public relations should be created.
- The emergency management system of national streets and highways should be integrated into the disaster plans of local and regional administrations.
- It is necessary to involve a psychological team directly on site.

Identify how/who gives the alert to whom

A disaster management system should describe the way alarm is given. This involves the description of the activity and equipment involved in that alert phase.

What has been learned following tunnel accidents is that:

- It is vital that the public may call for help using public emergency phones. Emergency phones must be installed frequently inside the tunnel. Together with the emergency phones there must be fire extinguishers. The removal of fire extinguisher should give a signal at the traffic control centre, and lead to immediate response. Combined with this automatic signal system, attached to the fire extinguishers there must be other fire alarm systems.
- Traffic moving into a tunnel where fire is developing must be stopped on the outside. This requires at least red light signals outside the tunnel entrance, and if the tunnel is long, red light signals should also be located inside the tunnel.

Identify what equipment is required for mitigating accidental scenarios,

Here is the main equipment for which it is necessary to be sure of their presence and their functioning when required:

- Ventilation
- Power supply
- Lighting
- Indication
- Detection
- Communication technical equipment
- Fire Fighting and other equipment
- Command Post

These are the points which are particularly important, according to the experience in France:

- During a fire accident, the smoke production is the largest problem for rescuers. Adequate measures must be taken to control smoke by ventilation[8].
- In many tunnels, the visibility of tunnel markers and cross-passage numbers should be improved (e.g. by fluorescent paint and enhanced lighting).
- Generally, during the fire fighting operations, light goes off. It is essential to dispose of an electrical generator and suitable emergency fire resistant lights.
- Equipment should be installed to make it possible to identify the location of the incident.
- Vital communication cables must be sufficiently protected. It is not acceptable that tunnel communication breaks down in case of fire.
- To remedy a big fire, the control centre needs to take rapid stock of the situation so that it can trigger the arrangements. For instance, an opacimeter will detect a large amount of smoke and the controller, assisted by centralised technical management including decision-support, will implement all the instructions laid down for such incidents : closure of toll stations, alert given to the emergency services at the plaza, information passed to the other plaza, activation of tunnel signals, public Fire Brigade alerted in both sides of the tunnel, activation of ventilation systems as appropriate, etc... The controller will try to "read" what is happening in the tunnel using all the means available to him: detectors, traffic surveillance cameras, verbal exchanges with the reliable information as possible must be gathered. Precise knowledge of what is happening will help for effective action.
- Automation of existing technology should serve to relieve control room operators of all simple tasks so as to leave their minds free for "high added value" work and enable them to bring their expertise to bear, in collaboration with the head of the emergency team.

Identify what information is needed for the different individuals involved

- No time must be lost in gathering and analysing the information, selecting a course of action, acting, and monitoring the operation as it proceeds.
- Detection devices, such as video monitor system, should be working under normal conditions all times. If the traffic control centre does not know what is going on they cannot take the adequate action.

Identify the training/exercises required for coordinating individuals in case of accident users, tunnel operators and rescues services,

The interest of having exercise is obvious, it allows for the individuals involved:

- to know each other better, and to get to know the tunnel itself better,
- to learn to work together, and improve the way the intervention could be performed,
- to have a common view of possible accident scenarios,
- to establish relevant procedure of intervention for real case situations.

From the lessons learnt from accidents, it is important to precise that :

- Simulation exercises can help to improve preparedness measures.
- Special training is required for the tunnel's own safety teams and for local public Fire Brigade whose services might be called upon: initial training for all new recruits and on-going training for everyone.
- The experience has shown that, in the first phase of intervention, the members of tunnel Fire Brigade and rescuers have already to know each other. Especially because, often, the fight against the fire has to start from both sides of the tunnel, at the same time interdependently.
- All Fire Brigades with responsibilities for fire and rescue operations in tunnels must pre-plan their operations. The plans must be co-ordinated with the police, the ambulance and healthcare service and the owner of the road tunnel.
- The development of scenarios is of vital importance to test whether and where the system is vulnerable. They can serve as a basis for procedures. The traffic controllers should be well trained to face accidents and follow the correct procedure, e.g. concerning evacuation, without creating panic.

[8] Depending on tunnel length and tunnel system, different ventilation concepts may be considered. If it is decided that transverse ventilation is necessary, transverse ventilation systems with exhaust air sucking are preferred. Available semi-transverse ventilation systems have the disadvantage, in the case of a fire, that the fans and airflow must be reversed.

- Of each possible scenario there should be a contingency plan. The emergency services should train to operate in actual structures and exercise with realistic scenarios. Better training can solve problems in communication.
- Preparedness against tunnel accidents is now based largely on automatic detection of fires and incidents. Improvements have also been made to emergency equipment, including on-board heat cameras for driving in zero visibility, long-endurance breathing apparatus, and clothing giving slightly more protection against radiant heat. All these measures need to be tested during exercises to check their suitability and maintain them at peak performance. Everything needs to be tested : equipment, procedures, the behaviour of staff on duty in the tunnel, and, today more than ever, the attitude of the public. The fact is that a correct behaviour of the public is the main precondition for successful operation. Preparedness now needs to incorporate this factor through the use of appropriate signalling systems to guide the actions of all those using the tunnel.
- The experience gained in an accident may help in revising the emergency plan and reorganising the inspection and monitoring systems.

Identify lessons learnt from exercises to improve plans.

Exercises should be followed by appropriate discussions between the individuals to ensure that things to be learnt on various dimensions is performed. The type of lessons can regard the use of equipment, the difficulty of coordination, the difficulty of communicating and the difficulty for understanding sometimes the rationales behind individuals actions.

Identify the activities to be audited for ensuring the maintenance of operational readiness

Like in other management systems, the audit is a critical activity that consists in checking on a regular basis the level of compliance according to the activities planned and in identifying areas to be improved.

This applies especially to:

- The training of personnel to emergency response and alert,
- the maintenance and inspection of equipment that is in use only during emergency situations,
- the implementation of the lessons learnt from the exercises.

Disaster management system: conclusions

Such a system could be described in a manual and procedures. The system, once described this way, is somehow the description of its structure and how it should work.

The aim of such a system is therefore to provide the support needed for defining in advance and during real time operations the rules of interactions and how the whole system is working efficiently towards its goals. Obviously, what is prepared and written in manuals and procedures is however never what reality really is.

And in fact that “working efficiently” issue has been of great concern for organisation leaders and for organisational theorists. It raises the scientific question about the nature of individual, group and organisational interactions and coordination. This point is particularly salient in disaster interventions. Organisation theories can help us to see clearer in that respect.

Organisation studies and particularities of emergency intervention

The understanding of organisations has greatly evolved during the last century, expressing the various dimensions of organisations.

Indeed, starting with a rational approach defining organisations as functions, responsibilities, rules, incentives (a rather mechanistic view) to a more elaborated approach including other dimensions addressing human nature - where organisation are seen not as rational machines anymore - made the organisation look like a more complex phenomenon.

Through the introduction of human relation (E.Mayo, 1924), but also the introduction of the bounded rationality nature of the individual decision making (Simon, 1957), to the impact of the environment on organisations, the picture is today more elaborated, richer. These evolutions led to deeper insights, deeper understandings.

Thus, today, various dimensions are now acknowledged to be of relevance for the understanding of organisations, they make the organisation more “natural” than rational, though both views can be considered complementary.

The concept of culture (E.Schein, 1992, R.Sainsaulieu, 1995) for example is one of these important dimensions and is closely linked to the cognitive, psychosocial and sociological side of human activities. Another key dimension is the political processes and the weight of individuals/groups interests in the way objectives of organisations are defined and ensured (Crozier, 1977, Friedberg, 1993), in a sociological perspective.

Organisations can be described through different lenses, revealing each time a different aspect of the richness of human interaction.
These issues are addressed for normal and daily operations of industrial plants for instance, and most of the organisational studies are therefore based on these kind “stable” organisations. They can appear quite rational, because things are established in advance, and even with a “natural” dimension, the activities remain over time and researchers can take time to study them. They can indeed stay in the organisation for a long time, interviewing people, observing, taking notes over time and discuss about daily activities with people.

However, emergency interventions, requiring the sudden coordination of several individuals, groups, are organisations that are made up under certain circumstances, could be called “incident organisations” (W. Smith, J. Dowell, 2001).
The differences between industrial plants for example - where responsibilities, functions, work plans and schedules are defined and experienced on a regular basis - and these "incident organisations" - where a shared experience is not often available to the individuals involved - makes coordination issues a really hot topic.

These “incident organisations” are therefore very specific compared to more traditional organisations. Some salient features can be pointed out:

- Major accidents are rare events. Opportunities for individuals, groups and organisations to experience real operational situations are then rare (apart from exercises opportunities).
- The objectives of the emergency intervention could hardly be defined in a comprehensive manner before. There are many potential scenarios which can possibly occur, and course of action will always depends on specific cases that are often not planned (P.Lagadec, 2003). L. Clarke (1994) describes emergency as “fantasy documents” that are not really matching the identified scenarios and that are not enough well prepared for the real case situations. Many elements can indeed come into play and create added difficulties to initial plans like the lack of resources as stated in plans (personnel availability, equipment etc in the case of another event occurring at the same time for example) or the unexpected type of physical events implied (level of intensity of fire, domino effects etc) that is far more important than what was expected.
- Individuals, group and organisations involved in intervention are not interacting on a daily basis. The consequence of this is that the effectiveness and culture of an “incident organisation” is therefore not the result of an experience shared through a long history of socialisation. E.Schein (1992) emphasises indeed that culture is “a pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and therefore to be taught to new members as the correct way to perceive, think, and feel in relation to these problems”. Many difficulties arising from this situation could be encountered and make intervention very specific moments of action.
- Moreover, specific cultures from various individuals must co-exist during the intervention phase. It is clear that each participants (individuals, group, organisations and in more general terms the institutions they represent) bring into the intervention their cultural background. Between fire brigade, police, medical staff, politics, industrials, each institutions that they represent brings different habits, assumptions, rationales about appropriate to solutions to problems faced.
- This high number of individuals may differ as well in their perspectives through what is at stakes for them (fire brigade, police, medical staff, politics, industrials have values to ensure etc). This can have an impact on the way operations will be run (it is a more political perspective).
- Considering the nature of this type of “incident organisation”, some key issues appear as well with the cognitive aspect of human interaction. Indeed, in many cases of emergency scenery, individuals from different institutions are remote from each other. They have therefore a partial picture of what’s happening. They must rely on description and understanding through communication and must take decision based on their mental representations. Sharing or not the mental representations through different participants in emergency situation is a critical point. K.Weick (1995) and the sensemaking dimension has shown how the situation representation greatly influences the course of actions, and how people were coping accordingly or

not to the situations faced. A specific study (W.Smith, J.Dowell, 2001) has emphasised these kind difficulties and the decision making process involved in such situations.

The disaster management system must acknowledge these potential issues. Actions could be taken to learn from the trainings/exercises to stress the difficulties that could be the result of such issues. For this learning to be enabled, these dimensions must be discussed following the exercises. This could help to elaborate on them and creating a knowledge, that could be shared. Such an approach is probably not an usual way of performing exercise debriefings. Some attempt to collaborate with specialists in human science could be of value to learn more about these issues, while people exchange following exercises.

Bringing the “natural” dimensions, as described earlier, into the study of coordination is important as these considerations affect in different ways, and always in a way very difficult to anticipate, the course of actions during emergency operations.

Conclusions

The social nature of organisation has to be acknowledged and the “incident organisation” – the disaster intervention – should try integrate these dimensions. The best practice would be to decipher these dimensions following exercise, when everybody involved in the exercise discuss about it.

Training techniques and simulations

To support training and exercises, simulations have proven to be effective tools. Simulations vary from simple to complex. For example, only paper, pencil, phone and a conference table may suffice in some cases. More complex (in terms of the technology required) is a complete virtual reality tunnel where scenarios can be played out. In some cases, one may choose to close the tunnel temporarily and perform an exercise on-site.

The choice of training tools depends on

- training goals (operating skills, incident handling skills, communication between organisations, try out procedures),
- number and type of participants (only operators, tunnel owner's management, operator and rescue services?)
- means available.

An effective tool may be a work station that is not in use and can be used by the operator to practice the operation of tunnel equipment.

In Holland, an RWS division provides a calamity centre used to practice emergency situations. One room contains a realistic traffic control station. In adjoining rooms, other officers such as the chief of the fire brigade, a police chief, or actors impersonating them, can use telephone or e-mail to contact the operator or each other. Emergency scenarios can be used there to exercise incident handling procedures away from the actual work place. Space is also available for evaluating the results with the entire group.

TNO developed an operator training programme for the Westerschelde Tunnel organisation. The operator sits at a desk similar to the normal operator's desk. Incident scenarios start and have to be handled in the correct manner. The system provides feedback: it lets the operator know if he has chosen the best option, the next best option, et cetera, in response to what happens. This proves to be an effective tool in procedure performance: as a consequence the operators can handle incidents based on their skills rather than having to use a procedure book. If an exercise leader is present, he may complicate this with, for example, a phone call from a "distressed tunnel user".

If, however, participants want to practice communication between operator and the on-site commanding personnel of rescue services, other techniques may be more effective. For this purpose, for example, an exercise leader may direct an incident scenario with the participants in a conference room. The exercise leader provides the incoming information about what happens in the tunnel and the participants respond to this information by saying what they would do.
On-site realistic exercises involving all relevant participants may be especially useful for testing procedures.

Cognitive support

To prevent cognitive overload, support systems should be designed that help the operator in assessing the situation and making the right decisions. During high-demand situations, there can be an enormous number of incoming alarms and information. This makes it difficult for the operator to form an accurate picture of what the cause is. Besides that, emergency situations do not occur very often. This means that the operator has no routines in following the right procedures and taking the right actions. Neerincx (2003) [[1]] describes a number of cognitive support functions that can help the operator during crisis situations. Although these functions were initially designed for a ship's bridge, the functions are also applicable within the domain of the tunnel operator. These functions are: information handler, rule provider, emergency scheduler and diagnosis guide.

Information handler

In order to enhance the situation awareness of the operator, an information handler should be used. It presents an overview of the tunnels state and alarms. The information is organized according to the tunnels structure and the current events. For example, a schematic representation of the tunnel could be shown, indicating the sector where the incident is including status, alarms and tasks that have to be performed.

Rule provider

A rule provider supports the operator by presenting the procedures and rules that have to be followed under specific (high-demand) situations. At the same time, it shows the status of the procedure that is followed. For example, in case of an accident, the procedure could be: activate warning signals and speed reduction in tunnel, close the obstructed lane, close the tube, call emergency response team, etc. The rule provider shows this list in the right order and indicates what actions are completed and what action still have to be done.

Emergency scheduler

The emergency scheduler prioritizes alarms that have to handled first. For example, in case of fire, evacuation of tunnel users may have the first priority before attacking the fire. By showing this, the operator knows in which order the alarms should be treated.

Diagnosis guide

A diagnosis guide supports the operator in analyzing the symptom-cause relation of alarms that are generated. The system can show a list of possible causes of a set of presented alarms. For example, the order in which smoke detectors switch on can reveal the location of the fire and the direction of the smoke stream. Speed detectors give alarms when, for example, the traffic speed drops below 50 kph. These detectors give information about the direction in which the cue develops itself. This also indicates where the fire is. With this information, the operator can be advised how to respond. For example, when the smoke stream is moving towards the cue, the ventilation system should be switched on to keep the smoke away from the tunnel users.

Command groups and the calamity button

A calamity button is a command group that enables the operator to save time in an emergency by taking a number of actions pushing only one button. The commands grouped under the calamity button are commands for (almost) all calamity scenarios.

Dutch tunnels usually have unidirectional traffic and thus consist of at least two traffic tubes. Most tunnels have longitudinal ventilation. A calamity button for a Dutch tunnel may start the following actions:

- Close the entrance of the incident tube and the one that is used for access by the emergency services (usually the tube next to the incident tube in the opposite driving direction) using the traffic lights;
- maximize light level in both traffic tubes;
- start longitudinal ventilation in tunnel tubes;
- prepare escape route:
  - if necessary, unlock doors;
  - start ventilation in escape route;
  - maximize light in escape route;
- start pumps for fire fighting system;
- block all drainage pumps.

An example: Westerscheldetunnel (Rypkema et al, 2002): for each of the unidirectional tubes there is a calamity button:

- close tunnel entrance (traffic lights)
- direct all traffic to right lane
- lower speed limit on right lane
- adjust ventilation
- maximize lighting level
- prepare escape route:
  - start ventilation in connecting passages between the two tubes
  - switch on extra lights for escape doors
  - warn drivers in safe tube: “pedestrians on road”
  - unlock escape doors
- start pumps for fire fighting system;
- block drainage pumps.

Another example: in the control centre of the Kiltunnel, for each of the unidirectional tubes there are two calamity buttons: one for any incident that is more than a disturbance, and one that is activated only if there is a fire.

One step further

One step further than a command group is an automated response. In this case, when sensors detect certain circumstances in the tunnel, appropriate measures are activated without the intervention of the operator. For example: if fire is detected, the ventilation is automatically started.
Of course, possible consequences have to be thoroughly analysed. A tunnel owner will have to make absolutely sure that a certain response to a certain detection can never have undesirable effects. Additionally, it has to be possible for the operator to undo the response after it has been automatically activated.

Facilitating the evacuation process

Many measures can be used to guide tunnel users on foot towards a safe place. Ideally, the operator should be able to activate these measures with one single action. He should also be able to see when each of the measures is fully operational and whether there are any malfunctions.
For example, in some cases, tunnel users have to flee to another traffic tube. In such cases, the escape doors are locked until there is no more traffic driving in the other traffic tube. Tunnel users that go to an escape door and find it locked, have to be informed about this to prevent them from trying to escape the wrong way. This is a task for the operator.

Two other techniques to assist in the evacuation process are described here.

Previously recorded announcements

If there is a fire in the tunnel, a serious threat is posed by the so-called wake up time of the tunnel users. Based on studies of human behaviour in tunnel incidents, the general response to smoke on the outside of your car is: to ignore that there is a problem and stay inside (Papaioannou & Georgiou, 2003; Boer, 2002). The car appears to be a safe place in the beginning. Persons do not leave their car until it is too late, when they are unlikely to survive the walk to an escape door. Based on the same studies, announcements by the tunnel operator are effective in activating the tunnel users and starting the evacuation process (Boer, 2002).

Therefore, it is essential that:

- announcements are broadcasted quickly through all available channels (local radio frequency and speakers in tunnel);
- instructions are clear and correct;
- instructions include warning other drivers.

In some tunnels, the operator can select an announcement on his computer. An announcement, previously recorded in several languages by professional native speakers, is then broadcasted. This approach has several advantages:

- the instructions given are correct for the situation and based on the available relevant procedures;
- the announcement can be easily understood, because they are professionally recorded, for example by radio reporters;
- the announcement can be recorded in more than one language;
- the announcement is pronounced more calmly and with more authority, generating a more effective response;
- the operator only needs the time to select the correct message and push the button.

Of course, the operator always has to be able to talk to a tunnel user because one can never predict exactly which messages will be necessary.

Sound beacons

In additions to arrows and pictograms, both of which are visual signals, sound beacons are a relatively new way of guiding tunnel users on foot towards escape doors. This is especially useful in smoke. Sound beacons are successfully used in (military) ships and mining industries. However, these beacons generate a noise that is not necessarily perceived in the right way by an inexperienced person, such as a tunnel user. If you do not know the sound, which resembles machine noise, it will most likely repel persons instead of attracting them.

Ordered by RWS Centre for Tunnel Safety, TNO has developed a new type of sound beacon with a different type of sound (musical chords) and a short message (such as "exit here") (Boer & Withington, 2004). Tests have shown that, if a sound beacon is mounted above an escape door, most people can find the door, even in dense smoke.

If applying sound beacons, additional measures will have to be taken: for example: if the operator wants to broadcast an announcement, the beacons will probably have to be temporarily suppressed. This can be done automatically, for example by linking this suppression to the intercom button. Also, the operator may in some occasions need to instruct the tunnel user to go towards the sound and to inform them that the sound beacons will lead them to an escape door.

Appendix 9: Data sheet for innovative evacuation system

Because of the length of this appendix, it has been compiled using numbered headings, for ease of reading

Introduction

This appendix has been written in the form of a **data sheet** for the *Fire Detection and Evacuation Beacon* system, which was developed under this European 5th Framework Research Programme for 'Cost-Effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels': UPTUN. This document describes **engineering prototypes** that comprise a 'proof of concept' demonstration system.

A product name has not yet been devised so, throughout this datasheet, the system will be referred to as the 'UPTUN beacon'. It should be noted that this is only a temporary designation.

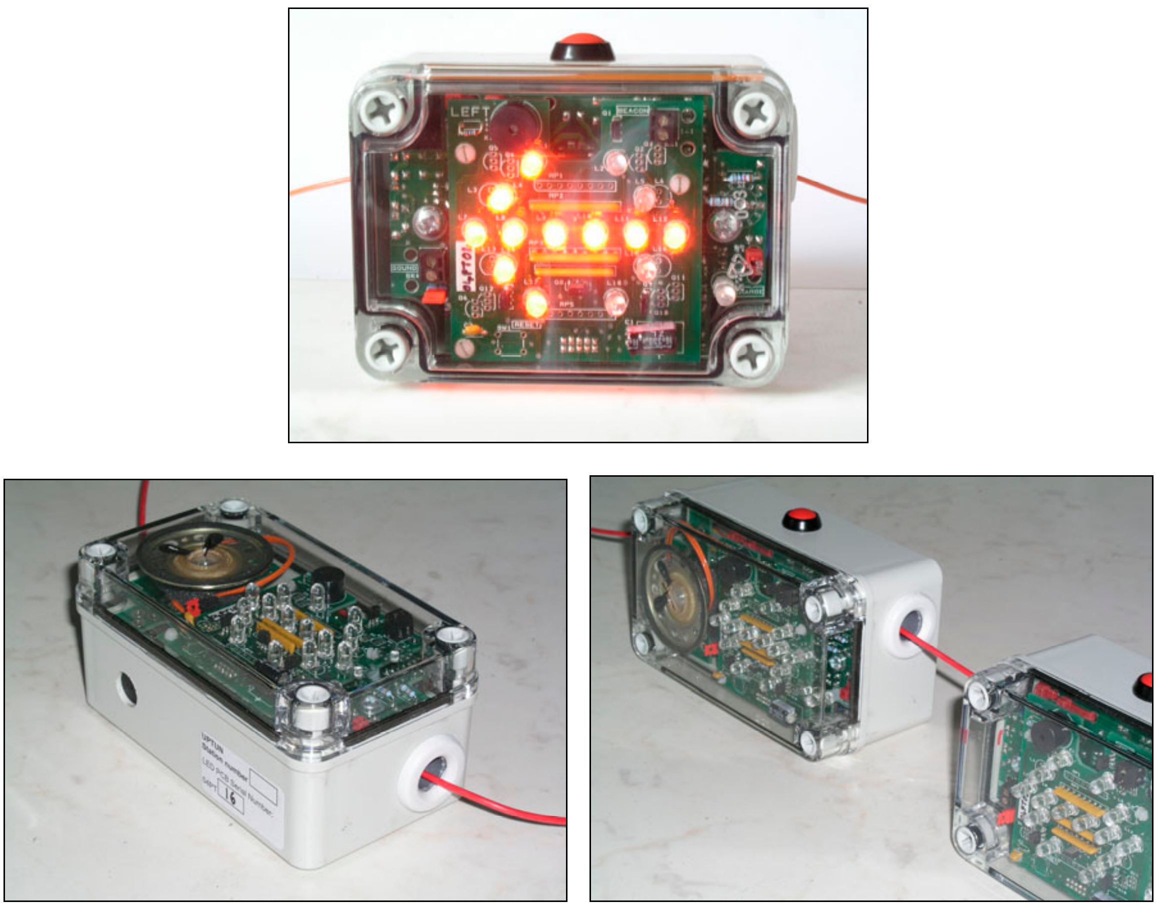


Figure A9-1 : Photos of assembled UPTUN beacon

Top: the smaller *Type I* enclosure. The Attention Switch is central on the top side of the box
Above Left: *Type I* enclosure in foreground; *Type II* enclosure, with sounder, in background
Above Right: *Type II* enclosure. Sounder is visible on face of box; carbon monoxide sensor port on bottom side

Glossary

ADC Analogue to Digital Converter

ASK	Amplitude-Shift Keying
BPSK	Binary Phase-Shift Keying
BTL	Bridge-Tied Load
CLB	Command Line buffer
CO	Carbon Monoxide
EEPROM	Electrically Eraseable/Programmable Read-Only Memory
FSK	Frequency-Shift Keying
GUI	Graphical User interface
JS	Javascript, a web scripting language
MCU	Micro-Controller Unit
OOK	On-Off Keying
PHP	A web scripting language
PIC	A range of MCUs sold by *Microchip*
PLL	Phase-Locked Loop
p-p	Peak to Peak
t.b.d.	to be determined
TIB	Terminal Input Buffer
UART	Universal Asynchronous Receiver/Transmitter

Product Overview

The UPTUN beacon system consists of four elements…

- A distributed set of addressable ‘outstations’
- An induction loop to provide communications and to distribute power to the beacons
- A control unit
- A graphical user interface (GUI) and database

These elements are shown in ***Figure A9-2***.

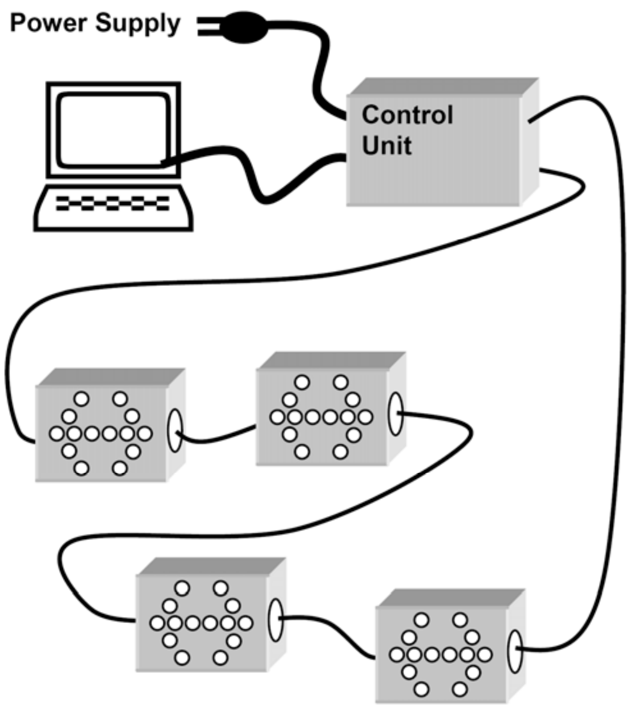


Figure A9-2 : Elements of the UPTUN beacon system

The UPTUN beacons are threaded onto a loop of wire. They receive power from this loop, use it transmit and receive data, but there is no electrical contact with the loop. The induction loop is driven by a control unit, which communicates with a computer terminal via a serial data link

Outstations

Fire Detection

The outstations provide a fire detection facility by monitoring the local **carbon monoxide** concentration and temperature and transmitting this information to the control unit. The processing of this information can reveal trends in CO concentration and temperature that is indicative of an imminent ‘thermal event’ before smoke and flames become detectable. The deployment of a number of outstations allows the implementation of a distributed fire detection capability.

A digital filter within the microprocessor in the outstation provides noise filtering and, additionally, increases the effective resolution of the CO sensor. When a fire has developed and there are significant concentrations of CO, the outstation can be switched to a less sensitive range to monitor fire development and to infer toxicity from the products of combustion.

This, together with the **precision temperature sensor** measurement, can provide information as to whether the tunnel/building environment remains life-supporting for its occupants. In turn, this information may help determine whether rescue is feasible.

Way Finding

The outstations also provide visual and audible **way-finding** in low-visibility conditions by means of high-brightness LEDs and a high-efficiency sounder. The alarm condition is initiated by the control unit, but it will also occur if a beacon loses communication with the control unit.

Connection of Multiple Outstations

The outstations are individually addressable by the control unit, which can thereby configure an outstation for a certain action, or request it to report back with status information and other data it has collected.

The outstations are, essentially, threaded 'in series' on a single wire loop that is terminated at the control unit. However, an important and novel feature of the system is that the beacons do not make physical contact with the connecting wire. Instead, the outstations receive power from the control unit, to charge their internal battery, by inductive coupling – see ***Figure A9-3***. Additionally, data is transmitted and received by inductive coupling to the wire.

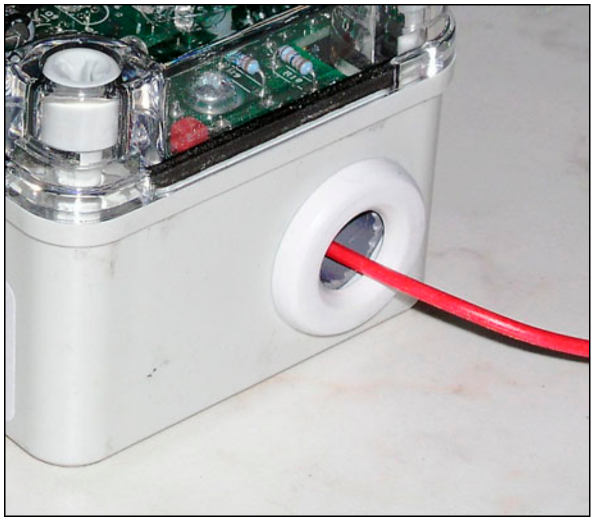


Figure A9-3 : Photo of outstation showing non-contact method of coupling to the communications / power line

The moulded boss mates with an ABS pipe, which runs through the enclosure, thus ensuring that the enclosure remains fully sealed

This contact-less system has a number of advantages…

- External power provision by inductive coupling avoids the need to supply power cables to each unit
- Inductive coupling of data avoids the need for multi-wire data cables
- The design offers fail-safe behaviour, with each beacon activated when the charging line is broken or de-energised
- Serial nature of connection guarantees charge-current sharing
- Contact-less system confers electrical isolation of individual units
- High environmental protection standards can be addressed (including submersed operation)
- Simplicity of installation and opportunity for temporary deployment
- Possibility of using the outstations to power and take readings from external sensors

Control Unit

The induction loop is supplied with a high frequency alternating current by the control unit. The design of the loop driver uses a current-controlled power amplifier, which is guaranteed to be stable under all load conditions.

For the engineering prototype, the loop current is regulated to, typically, 340mA rms. at a frequency of around 3.6kHz. This results in a typical voltage drop of 120mV rms (340mV p-p) across each outstation, and a charging current of typically 5–8 mA.

The driving capability of the Control Unit is 11V r.m.s. (30V p-p) and so the current engineering prototype will drive up to about 80 outstations. With improved heatsinking, the driving capability can be increased to more than 35V p-p, allowing 100 or more outstations to be connected to a single loop. The maximum address capacity of the system is currently 128 units per loop although there is, in principle no reason why this cannot be greater.

Data is transmitted to the outstations using amplitude-shift keying (ASK; also known as on-off keying – OOK) of the induction loop current. For the engineering prototypes the data is in a standard 8-bit serial format, as used by RS-232 data links, at 300 bits per second, although other serial formats are under consideration. The inductive pick-up in the outstations uses a ferrite toroid and a tuned circuit. To avoid problems with 'ringing', the serial data transitions are synchronised to the a.c. charging current waveform using a special synchroniser circuit. The use of a sinusoidal drive waveform in conjunction with this synchroniser ensures a low level of radiated interference. The low EMC signature will provide a 'stealth' capability against external detection, which is required in some specialised applications.

The outstations transmit data by superimposing a 25kHz frequency-shift keyed (FSK) serial data stream on the wire loop. The control unit demodulates this using a conventional phase-locked loop and provides a serial RS-232 output for the user interface. For the engineering prototypes the return data rate is 300 bps, although higher data rates are possible.

The control unit interfaces to the controlling computer using a standard RS-232 serial connection.

Although it is intended that the system be controlled via a graphical user interface, it has been designed so that the 'low level' serial command structure is accessible via a 'dumb' terminal. This approach to the design allowed us to debug the outstation software without requiring intensive GUI programming to be undertaken at the same time.

This data sheet is the data sheet for the UPTUN beacons and so it documents the low-level data structure. In a complete system, it is not intended that the user has access at this level. It is intended that the system be controlled by a GUI, developed separately.

Graphical User Interface

The purpose of the Graphical User Interface (GUI) is to present data to the user in a way that is easy to interpret, and to allow the user to control and program the beacons in a straightforward manner.

The GUI is based around a web server. This provides the twin facilities of delivering web pages to the user, and communicating with the control unit via the serial interface. A high degree of functionality is obtained by means of a database, in which the outstation data is stored, and by using server-side scripting in the PHP language, combined with client-side scripting in Java Script. One reason for this approach is that system operators at all skill levels will be familiar with the look and feel of web pages.

Implementing a GUI on a Windows™ PC does have a difficulty, in that communication with the serial port is not easy to achieve. Perhaps the best option is a dedicated Visual Basic program that appends data to the database, which it shares with the PHP module in the web server.

An alternative is to make use of a web server application such as **EzCom2Web** written by Cosmin Buhu and available from **www.easyvitools.com.** However, using this package as part of a high-level GUI is not straightforward . The product comprises a trimmed down web server, which runs on a PC. Web pages that include scripting commands to access the serial ports can be called up from the user's browser. Arguments are passed to the serial port using query strings appended to the URL. For example, to send the string "hello world" to the serial port, the user might enter the URL **http:// 127.0.0.1:8080 / webterm.esw?tosend=**

hello%20world where 127.0.0.1 is the 'localhost' recognised by the web server and **webterm.esw** is the page that includes the scripting commands. Data is received from the serial port by arranging for the scripting page to write a new web page dynamically.

We have achieved some level of functionality by incorporating a second web server (Apache) and using additional scripting in PHP and Javascript (see ***Figure A9-4***). However, this approach is not ideal. This method is not covered further in this document.

With the transfer of the serial data to the database handled by some special means, the remainder of the system uses relatively simple and widely understood programming methods. Programs written in HTML, PHP, Perl and JS can often be run on a variety of different computer platforms, and the programming challenges can be tackled by web-designers rather than necessitating the use of programmers with more specialised skills. This was felt to be essential because the design of the GUI will depend very much on the type of application in which the beacons are to be used; so much so that each customer may require his own specialised interface.

The design and use of a GUI is not covered further in this datasheet. This datasheet describes the operation of the beacons and the control unit at a low level. It is not intended that the end user will use the low-level commands described here. Instead, the intention is that the web server will issue commands on a continuous or selective basis to gather data from the outstations.

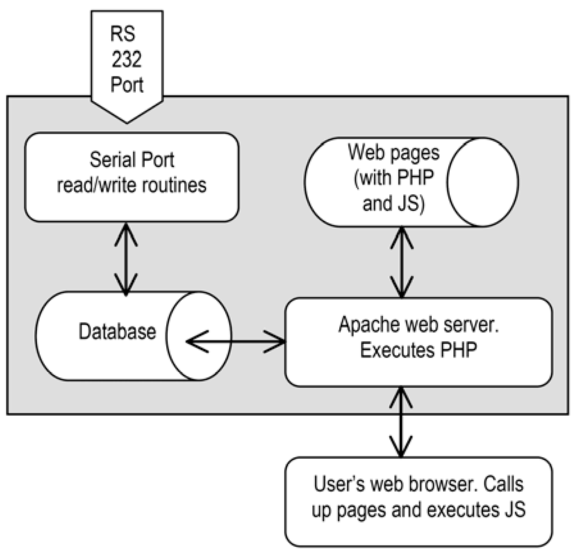


Figure A9-4 : The software modules that comprise a trial Graphical User Interface

For clarity, this diagram does not show the second web server that handles the serial port routines

Example of operation

A GUI issues 'background' commands to the outstations in order to collect data on carbon monoxide levels from a large number of outstations. This data is stored in a database, processed, and the results (e.g. levels, trends) delivered to the user as a web page.

Without this user interface, a low-level command will simply cause one beacon to return one CO reading on demand.

Other Applications

The contact-less method of power transfer and telemetry employed by the system suggests that it will have application in a variety of situations where extremely hostile environments are present, or where conventional electrical connectors are either unsuitable or unreliable. With suitable mechanical seals, the outstations and inductive supply line will operate in a submerged environment. Specialised applications of submerged low speed telemetry systems are discussed below. These further highlight the unique design aspects of the system.

Specialist inductive modems are already deployed for oceanographic measurement purposes (e.g. **www. seabird .com/products/spec_sheets/44data.htm**). However, these systems are point-to-point and require the submerged subsystem to have its own on-board battery or other local power supply arrangement.

The system we have developed offers the opportunity of an array of sensors or detectors with both power and telemetry supplied in a contact-less fashion by a single insulated cable.

At modest depths (for example harbour or estuary environments) total encapsulation of the existing outstation mechanical design may well be sufficient. This offers the prospect of a low cost, rapid-deployment power and telemetry arrangement for immersion at shallow depth.

The same system, because of its extremely low radiated emissions, would have high inherent stealth capability. One speculated application is the possibility of equipping the outstations with sensitive magnetometers or other sensors to offer a 'perimeter fence' detection capability across harbours or other vulnerable installations. Whilst these applications are merely speculated, the underlying system concept is technically capable of operating in an above-ground, tunnel or submerged environment.

Less specialised applications include low-speed telemetry systems for use in extremely hostile environments, where conventional electrical connectors are either unsuitable or unreliable.

Beacon Specification

<u>Functionality</u>
A block diagram of the outstation is shown in ***Figure A9-5***.

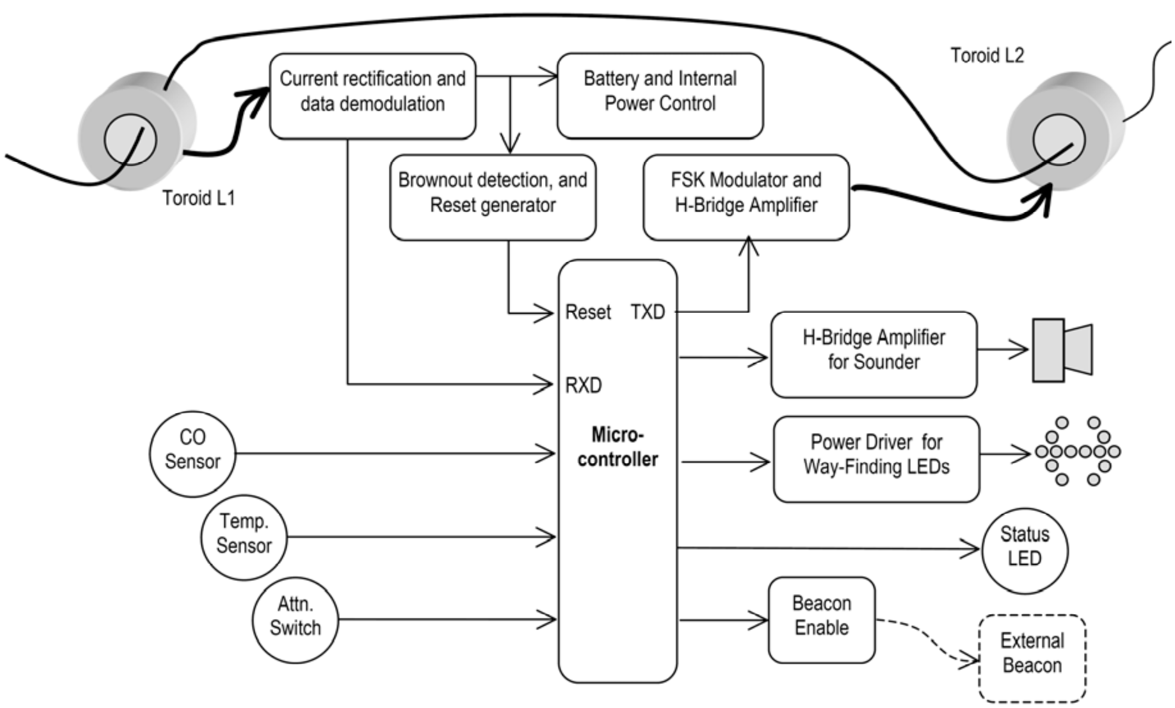


Figure A9-5 : Block Diagram of UPTUN Beacon

During normal operation, the induction loop wire carries an a.c. current of around 360mA rms. This causes a smaller current to flow in the toroid L1, which is rectified and fed to an on–board rechargeable NiMH battery, which provides backup power when the line current fails.

The line current is modulated with serial data. The demodulated data goes to the microcontroller (MCU) UART data receiver.

The outstation is designed to initiate an alarm condition when the induction loop is broken. The alarm will drain the battery fairly quickly, and the battery will recover its voltage only slowly when the line current is restored. Due to this 'soft' nature of the power supply (slowly varying voltage over wide range) it is necessary to use a well-defined brownout / reset generator external to the MCU.

The MCU has a number of analogue and digital inputs, and digital outputs, which are described in §A9.3.3, Sensors and Indicators, below.

The transmit data output controls two tone generators, to produce a frequency-shift keyed (FSK) signal which is superimposed on the induction loop by means of an H-bridge driver and the toroid L2. When the MCU UART is not transmitting, the FSK generator is switched off and the H-bridge is clamped so that it does not load the line.

Enclosure

- Sealed (IP67) polycarbonate box
- Transparent lid for viewing Direction LEDs

Enclosure type:	**Type I**	**Type II**
Width	110 mm	140 mm
Height	80 mm	
Depth	65 mm	
Fixing centres	t.b.d.	
Internal diameter of inductive coupling tube	15 mm	
Weight	400g	480g

Sensors and Indicators

- Carbon Monoxide Sensor †
- Temperature Sensor
- Attention Button
- High-Brightness LED Direction Arrows
- Status LED indicates outstation activity
- PCB-mounted beeper
- High-volume sounder †
- Output for external device, e.g. Xenon beacon
- Expansion facility via PCB connector
- Provision for additional internal battery

† symbol indicates feature is only present on the larger Type II housing.

Temperature Sensor

Type	Silicon IC
Manufacturer	National Semiconductor. Part: *LM35DZ*
Location	PCB-mounted
Useable Operating Range	0°C to 80°C
Resolution	0.1°C
Accuracy	0.5°C (typical)
Response Time	Slow: governed by thermal properties of housing
Self-Test Facility	no
Noise Filter	Optional first-order low-pass filter with time constant of 32s (1/200 Hz)

Carbon Monoxide Sensor

Sensor type	Electrochemical: a small electrical current is generated during the oxidation of CO to CO_2
Manufacturer	Monox Ltd; **www.monox.com** Part: *Compact-S*
Location	Mounted on housing, with breather hole venting inside housing
Response Range	0–5000ppm
Ranges Available	0–200ppm / 0–2000ppm
Resolution	0.2ppm / 2ppm
Accuracy	3ppm / 5% linearity
Response time	< 2 min (90%)
Operating Temperature	-20 to +50°C
Operating Lifee	5 years
Self-test current	1.33mA (see below)
Self-test time	20s, user adjustable
Absence of sensor	Reported as ≈ –20ppm (Sensor is not fitted to type I enclosures)
Noise Filter	Optional first-order low-pass filter with time constant of 32s (1/200 Hz)
Auto-zero	Sensor output can be zeroed in software

The CO sensors have a built-in self-test feature. Passing a controlled current into the test pin causes the cell to generate a small amount of hydrogen, which reacts in a similar way to CO. The outstations will accept a self-test command and the response of the CO sensor can then be monitored. Further information about the CO sensor can be obtained from technical documents on the manufacturer's web site.

Note: On the engineering prototypes, the CO Sensor and the Temperature Sensor share the same software digital filter, so the outstation cannot be configured to filter both simultaneously.

Attention Switch

An ‘attention’ switch is mounted externally on enclosure. During normal operation, this switch can be interrogated by the Control Unit, which can then report whether it has been pressed.

The outstations do not initiate communications with the control unit; they only respond to an interrogation. It is therefore important to note that if the user requires this switch to have an ‘emergency’ action, he must arrange for frequent polling of the outstations. The switch cannot be interrogated when an alarm condition is present.

This switch is also used during the process of allocating addresses to the unit.

Pressing this switch will result in the status LED being illuminated. This does not indicate that the operation has been acknowledged by the Control Unit.

LED Direction Arrows

This is an array of 14 high-brightness red LEDs for direction arrows, ← and →. The frequency and pattern of the flashing can be controlled by the user. See §A9.3.4, Alarm Mode.

Provision for alternative indicators based on side-viewing red and green LEDs.

A particular feature of the UPTUN beacons is that the flashing of the LEDs can be synchronised between units. Additionally, it is possible to delay the flashing by a fraction of a second, and this value is programmable independently on each beacon. The result is that it is possible to achieve a running light effect where a flashing light appears to move down a passage.

Status LED

A ‘status’ LED indicates charging and other conditions. When the units are connected to a live line and the internal battery is charging, the status LED will blink briefly every 4s. When commands are received by an outstation it will blink rapidly whilst the commands are being processed.

PCB-mounted bleeper

This is intended as an installation aid only

High-volume sounder

A high-volume beeper is mounted in the enclosure. It is intended that the frequency and pattern of the alarm can be controlled by the user, although these options are not available on the present issue of software. A number of different tones –pure and ‘warbled’ – and a noisy ‘hiss’ are programmed into a look-up table in the MCU.

Type	8Ω 50mm Mylar speaker
Driver	MOSFET H-Bridge (i.e. Bridge-tied Load (BTL)). Nom. ±5V

Output for External Beacon

There is a switched output, on the PCB, for activating a self-powered Xenon beacon or similar.

Driver	Transistor switch. Rating t.b.d.

Expansion Facility

A PCB-mounted 2mm-pitch 'Milli-Grid' connector (Molex part 87089-1016) is provided to allow a daughter-board to be fitted, offering additional inputs ands outputs for sensors and indicators. This connector is not fitted on the engineering prototypes.

Additional Internal Battery
There is provision for an additional internal battery.

Note: Although provision has been made for an internal battery, there are additional issues to be considered before this facility can be used with the engineering prototypes.

Alarm Mode

An alarm is initiated when the loop current drops to zero for three seconds. In future versions of the software the delay period prior to actuating an alarm will be programmable, hence the immunity to false alarms can be tailored to the application.

When the loop current is restored, the beacons will 're-boot' and so operation continues from a known software state. This means that a brief, controlled line drop can be used to re-boot the system without sounding the alarm.

During an alarm condition…

- LED Direction Arrows blink
- Sounder is activated
- External Beacon is activated
- Outstation will not respond to commands

An alarm is cancelled when…

- Line current returns; re-booting the outstation
- Internal battery becomes exhausted

Further information on the Alarm Mode is given in §A9.4, Operating Modes.

Communications

Physical Level

- Asynchronous serial protocol (RS-232)
- Receive data modulates a.c. power waveform
- Transmit data is FSK on low frequency carrier

	Receive	**Transmit**
Data Rate	300 bps (#1)	300 bps (#1)
Data Format	Standard RS232: 3 start (#2) – 8 data – no parity – 1 stop	
Transport	On-off keying of a.c. power line (#3)	FSK signal superimposed on power line.
Logic zero	0mA (or t.b.d.)	22kHz nom.

Logic one	300mA nominal	29kHz nom.
Absence of Data	Logic 1	No transmission (#4)

Notes:

#1 The system has been tested with higher data rates.
#2 Extra start bits allow the phase-locked loop in the control unit to obtain a lock
#3 Synchronised to carrier
#4 When no data is being transmitted, the FSK modulator is disabled. In this situation ,the PLL receiver in the control unit will default to a logic 1

Command Level

Character Coding	7-bit ASCII (8 bit ASCII is transmitted)
Terminal Emulation	Echoback operation (but see §A9.3.6 below)
Command Structure	Human-readable character strings
Command Line Termination	CR or CR-LF
Error Detection	No parity bit, but optional checksum can be added to each line.

Further detailed information about character and command reception is given in §A9.6, Character Reception.

Addressing

Each outstation must be programmed with a unique address so that the Control Unit can interrogate individual stations. The Control Unit can address the outstations in three ways…

- Global Address – all units respond
- Zone Address – only a specified set responds
- Individual Address – a single unit responds

The outstations are not factory-programmed with an address; neither is the address 'hard-wireable' using programmable links. Instead, the outstation addresses are set by sending a series of global commands to 'set address' and by pressing the **attention switch** on the outstation that is required to respond. Further detail is given in A9.7.3, Command List.

For the current engineering prototypes, Zone Addresses are not supported, and the overall address range is **0–255**. Some addresses confer special features, as indicated in the table below.

Station Number	**Class**	
0	Monitoring Station	Terminal emulation is 'echoback'
1–127	Operational stations	No command characters are echoed
128–254	Not used	These are not valid addresses for

255	Default on cold re-boot [#1]	the engineering prototypes [#2]

#1 If the Attention Switch is pressed during a cold re-boot (i.e. when the Reset switch is pressed) the unit will power up as station zero. This facility was intended for use during development.
#2 Because 255 is not a valid address, a unit will only accept Global commands after a cold re-boot. The obvious command to consider is one that initiates the address-setting routine.

The above is only a brief summary. Further detail is given in §A9.6 and §A9.7.

Electrical Characteristics

Line Current	340mA rms at 3.4kHz (nominal)
Charging Current [#1]	2% line current, 7mA (nominal)
Line Voltage Drop [#2]	110mV rms (nominal)
Maximum Number of Outstations	Limited only by control Unit drive capability Present software restricts outstation identification addresses to range 0–127
Maximum Line Length	Limited only by control Unit drive capability. Typically several km
Internal Battery	**Nickel Metal Hydride 4.8V, 150mAh** Varta, part *4/V150H* A larger capacity battery is also possible (up to 1Ah).
Current Drain / Operating Time Off [#4, 5] Standby [#3] Reset [#4] Transmitting Alarm	(assuming fully-charged battery. See notes below) zero 300µA / 20 days 2mA / 3 days 75mA / 2 hours 150mA / 1 hour

Notes:

#1 Because serial data is transmitted to the beacons using OOK, a large amount of traffic will reduce the effective charging current
#2 The line voltage drop varies with charging current – see Figure A9-6 below
#3 The unit idles in a 'standby' mode with a low current consumption. However, it 'wakes up' eight times a second, for a few milliseconds, to perform housekeeping duties (e.g. real time clock, CO and temperature sampling). The unit also wakes up whenever the line drops to indicate the start bit of a serial data transmission from the Control Unit
#4 There is a design fault here. See §A9.8.1
#5 The Off state is selectable by a programmable link (the red 'tag' visible in the final photo of Figure A9-11). This allows a battery to be fitted in advance of the units being commissioned

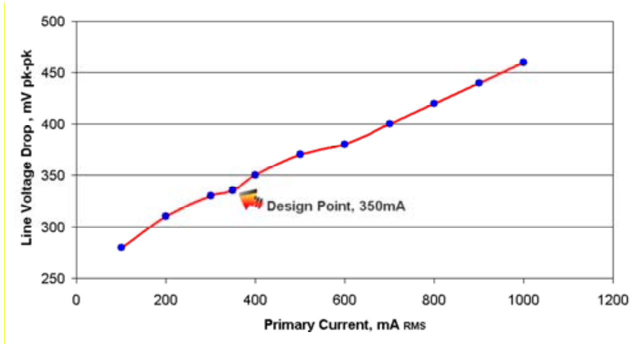


Figure A9-6 : Line Voltage Drop v. 3.6kHz Primary Current

The graph indicates that a higher charge current may be selected by increasing the line current. However, this is at the expense of a modest increase in line voltage drop, and a consequent reduction in the number of beacons that can be driven

Command Set

A full list of commands, and the command syntax is .given in §A9.7 of this document. Commands are provided to…

- Configure LED direction arrows (left/right/both/none)
- Set pattern and repetition rate of blinks
- Set frequency, pattern and repetition rate of sounder.
- Test the LEDs
- Test the sounder
- Read back the temperature
- Read back the CO sensor (high or low range)
- Test the CO sensor
- Read the status of the Attention switch

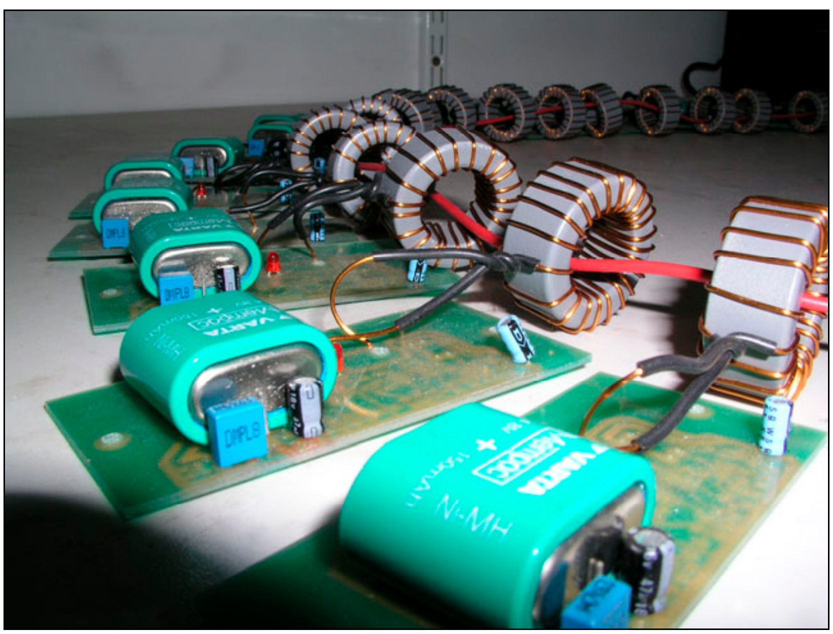


Figure A9-7 : Photo of early prototype

Around 40 of these primitive outstations were built in order to investigate the performance of the toroidal inductors. These units are receivers only. The line current charges the PCB-mounted battery and, when the line current is removed, a PCB-mounted LED flashes

Operating Modes

Alarm 'Patterns'

The various audible and visual alarm states can be distinguished by **patterns**. For example, the default way-finding alarm is to blink the LEDs with a double-flash every 1 second. The default audio alarm is a quad beep every 2 seconds. The patterns are user-programmable, with the programming amounting to specifying a 'pattern mask' byte that is logically combined with a count from the real-time clock. **Note:** The current version of the software does not support user-specified pattern masks.

Normal Running

During normal operation, the ***monitor LED*** blinks briefly every four seconds to indicate that the beacon is active and accepting a charging current. In this mode, the unit accepts serial data and acts on the commands.

Character Processing

When a serial character is received the monitor LED will blink rapidly at 4Hz. This indication is cancelled when the command line processing is finished.

Alarm Test

If the alarms are activated by a command to test them (as opposed to by an event that leads to ***alarm mode***) then the unit remains in its "normal" operating mode. Note that ADC processing does not occur whilst the sounder is active; and that UART operation might be sporadic or cause glitches in the sound generation.

Some of the commands result in the unit entering a long, timed loop. For example the CO self-test could tie up a unit for a minute or more, should the operator wish this.

Alarm Inhibit

When the communications and power line 'drops' the usual action is for the beacon to enter ***alarm mode***. However, there are occasions (e.g. during product development or system commissioning) when it may be useful to be able to disconnect the power line without the unit entering alarm model. A command is available which inhibits the detection of the line-loss condition. In this situation, when a line-loss occurs the unit sets the ***monitor LED*** to an infrequent blinking, and then carries on running (from the on-board battery) in ***normal mode*** using minimal power.

When the line is restored operation continues as normal. This is in contrast to the situation when the line is restored from ***alarm mode***, which triggers a re-boot.

Alarm Mode

Alarm Mode is initiated when the loop current drops to zero for three seconds. In future versions of the software the delay period prior to actuating an alarm will be programmable, hence false alarm resistance can be tailored to the application.

When the loop current is restored, the beacons will 're-boot' and so operation continues from a known software state. This means that a brief, controlled line drop can be used to re-boot the system without sounding the alarm. The re-boot is a 'warm start', where all the user's parameters are retained. (See below for further details).

Sustained Alarm Mode
After a period of time in ***alarm mode***, the alarm patterns are reset from their 'alarm' values to their 'sustained' values, which exhibit a lower duty cycle. This feature is intended to conserve battery power. The timeout period is user-settable but, at present, the sustained alarm patterns are not. On the current demo units the 'fall back' time is set to a very low value – see §A9.4.6.

Quiet Alarm Mode
Consider a cold start, as described in §A9.4.4.2, but where there is no line power present when the *battery* is restored, or the reset button is pressed. This situation will occur if a 'virgin' system is switched on before line power is supplied, or if the battery drains during an alarm situation sufficiently to trip the reset line and then recovers its terminal voltage.

Clearly it would be a mistake to activate the alarms in this situation, so the unit enters a ***Quiet Alarm Mode*** where the LEDs and Sounder are off, and the alarm pattern usually associated with the LEDs is displayed on the monitor LED.

Restoration of Line

When the power/data line is restored after a power failure the beacon responds with an action that depends on the history of the line restoration.

…from Alarm Mode
When the line is restored from an ***alarm mode*** condition, the software forces an error condition (a Watchdog timeout) that causes the unit to re-boot. This is a ***warm re-boot*** where the user's parameters are retained. After the re-boot, a visual and audible alarm sound briefly (see table in §A9.4.6).

…from Cold / Hardware Reset
If the line is restored from a state where the battery was absent, or if the reset button is pressed (accessible on development units only) the unit performs a ***cold re-boot*** which is similar to the warm start described above, except that certain parameters are set to default values. In particular, the station number is set to 0 or 255, depending on circumstances.

…from Normal: Alarm Inhibit Mode
In this situation, the unit takes no action because, in effect, it did not notice that the line had dropped.

Operating Modes – Summary

The various alarm conditions are summarised in the following table.

Condition	Direction LEDs	Sounder (pattern, pitch)	monitor LED
Normal Running	off	off	1/8 s flash every 4 s
Alarm test	Alarm-mode pattern [#1]	Alarm-mode pattern and pitch [#1]	1/8 s flash every 4 s

Character processing	off	off	off	4Hz flash
Alarm inhibit	off	off	off	Double 1/8 s flash every 16 s
Alarm Mode	user-specified pattern [#2]	user-specified pattern and pitch [#2]		off
Sustained	1/8 s flash every 2 s	1/8 s beep every 2 s		off
Line Restored from Alarm Mode [#3]	1/8 s flash every 1s for 3s	1/8 s beep every 1s for 3s	high (1748Hz)	off
Line Restored from COLD [#4]	1/8 s flash every 1s for 6s	1/8 s beep every 1s for 6s	high (1748Hz)	off
Quiet Alarm Mode (Line Absent during COLD start)	off	off		Alarm-mode pattern

#1 The default alarm patterns are the cold-start settings as listed below.
#2 These settings are not adjustable in the current version of the software; default to cold-start values.
#3 Stations send “Warm Start. Hello from station nnn”. This is a situation where, in theory, more than one station could be replying at the same time.
#4 Stations send “Cold Start. Hello from Station nnn”. The station number will be zero or 255 – see §A9.3.6, §A9.6.2.1 – because the station number is not programmed into EEPROM memory and is lost when a hardware reset occurs.

Warm and Cold-Start Defaults

Register Name	**Purpose**	**Warm-Start Value**	**Cold-Start Value**
Real-time clock	Timing	-3s ‡	-6s. (i.w. re-boot alarm sounds for 6s)
Skew	Running Light effect (see §A9.3.3.4)	†	0
SkewStepSize	Running Light effect (see §A9.3.3.4)	†	8
alarm_led_dir	Direction of Way-finding LEDs	†	left
station	Station number	†	0 or 255
alarm_timeout	Delay before sustained alarm mode	† ‡	$N = 1 \Rightarrow 10$ s [#1]
CO_selftest	Time for self-test current	†	20 s
led_alarm_pattern	Holds LED pattern for Alarm Mode	† ‡	double-flash every 1 second
audio_alarm_pattern	Holds audio pattern for Alarm Mode	† ‡	quad beep every 2 seconds
alarm_sound_type	Holds audio sample for Alarm Mode	† ‡	Half-frequency (874Hz) square wave
Filter_mode	CO Sensor digital filter	0	0
Keycount	Counts presses of attention switch	†	0
CO Range	CO Sensor range	High (2000ppm)	High (2000ppm)

† Value retained on warm start. ‡ not programmable by user in current software version.
#1 Programming a timeout of N corresponds to a time, in seconds of $32(N – 1) + 10$. The ‘development’ value for N is 1. The maximum alarm time is therefore about two hours and 15 minutes, before the unit drops back to the ‘sustained’ alarm mode

State Diagram

This diagram gives a representation of the operating modes discussed in the previous section.

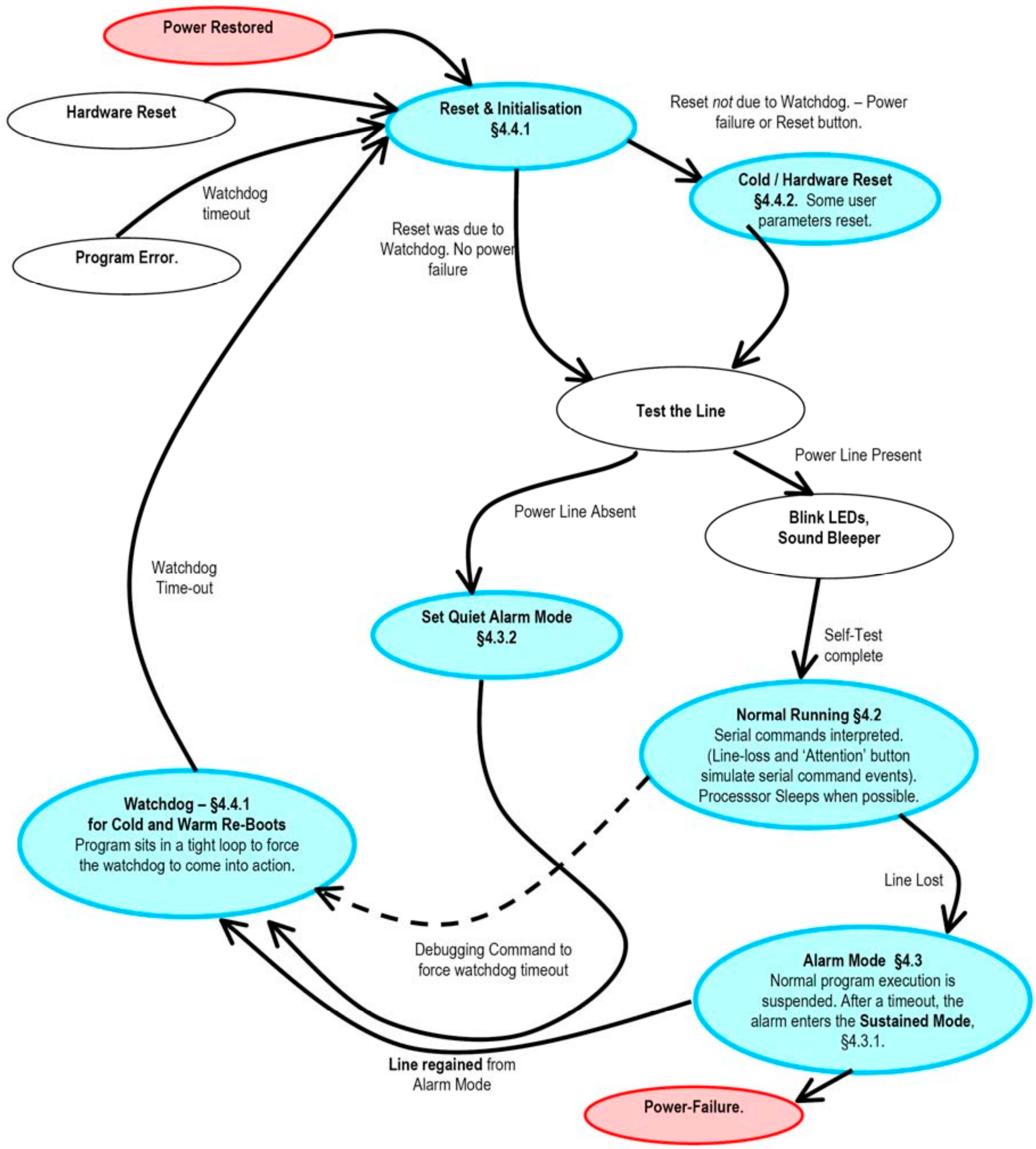


Figure A9-8 : State Diagram showing operating modes of UPTUN beacon

Control Unit Specification

Functionality

A block diagram shown in ***Figure A9-9*** below.

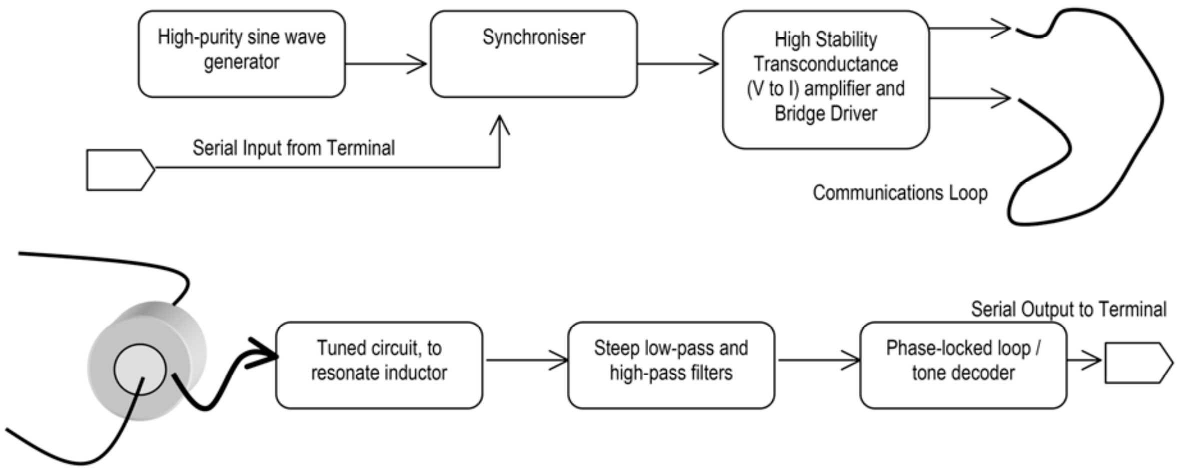


Figure A9-9 : Block Diagram of Control Unit

Transmitter
A 3.6kHz sine-wave generator drives complementary power amplifiers (the Bridge Tied Load principle) and uses current feedback to maintain the load current at 340mA. Particular attention has been paid to ensure that the amplifier remains stable whilst driving a floating load in a current-feedback (transconductance) configuration. The sine-wave is of a high purity in order to minimise EMC, and also to prevent interference with the PLL that detects the incoming FSK data.

The current is modulated by the serial data input from the host computer. The modulation is amplitude-shift keying (ASK), also known as on-off keying (OOK). The data transitions are forced to coincide with zero-crossings of the current waveform by means of a synchroniser circuit.

Further brief description was given earlier in §A9.2.2.

Receiver
A tuned toroid detects the FSK signal from the outstations, and this is demodulated using a phase-locked loop (PLL). The resulting serial data is sent to the host PC.

Specification: Serial Data

Voltage Levels
The design status of the Control Unit is that of an ‘engineering prototype’ and it does not, currently, use an RS-232 driver or receiver.

The receiver uses a discrete transistor inverter that drives a logic gate. The transmitter is an open-collector output from the PLL, with a passive pull-up to +12V. With the transistor on, this output will be slightly above zero volts, so it does not meet a true RS-232 specification. However, most RS-232 receivers should interpret this as a logic 1.

	Control Unit Serial Interface		**True RS-232**
	Receive	**Transmit**	
Logic Zero	+V t.b.d.	+12V	+V
Logic One	-V t.b.d.	≈+0.2V	-V

Connector
RS-232 commonly utilises a 9 or 25-way 'D' connector. These are cumbersome, especially when none of the control signals are required. The design status of the Control Unit is that of an 'engineering prototype' and it does not, currently, use such a connector. Instead, the signals are available on screw terminals.

For connection of the engineering prototype to a PC we have adopted a simpler connection method than that normally used. At the PC end we use a 9-way female D-connector, but this cable connects to a 3.5mm stereo jack plug, and the final connection to the control Unit is via an in-line jack socket. The corrections are listed below…

Female D plug	**3.5mm stereo jack plug**	**Reminder**
2 (RXD)	Ring	R for "receive data"
3 (TXD)	Tip	T for "transmit data from PC"
5 (GND)	Sleeve	insert

<u>Specification: Transmission to Outstation</u>

Serial RS-232 data is received from a PC and it modulates the induction loop current as described in §0 above.

Logic 1 representation	340mA rms at 3.6kHz (nominal)
Logic 0 representation	Zero current
Max Data Rate	600 bit/sec [#1]
Maximum Output Voltage	7.2V rms. 20.4V p-p
Maximum Number of Outstations	See §A9.3.6
Maximum Line Length	See §A9.3.6

<u>Specification: Reception from Outstation</u>

FSK data is received from the outstations as described in §A9.5.1.2 above. It is demodulated and sent as serial RS-232 data to the host PC.

Logic 1 representation	29 kHz (nom.)
Logic 0 representation	22 kHz (nom.)
PLL output for no lock	Logic 1
Time to achieve PLL lock	10ms (3 bits at 300 bit/s)
Max Data Rate	600 bit/sec [#1]

<u>Power Supply</u>

The engineering prototype requires stabilised power supplies of +18V and –18V @ 400mA.

Character Reception

This datasheet describes the engineering prototypes. In a customer-faced document, some of the detail of this section would be more appropriate in the 'engineering' section of the manual.

<u>Character Interpretation</u>

Characters transmitted to the outstation are received into a buffer (the ***Terminal Input Buffer***) but, with the exception of certain 'escape' characters, they are not processed further upon receipt.

The main program loop, "at its leisure" removes characters from the TIB and places them, one by one, in the ***Command Line Buffer***. When it encounters a carriage return it then interprets the line it has assembled in the CLB. If it encounters any errors it aborts interpretation and clears the buffer; then continues the process of copying TIB characters to the CLB. The following flowchart summarises the action, but is not an exact representation of the program.

<u>Echoback of received characters</u>

Special Station Numbers 0 and 255

Because the commands are received by all units, there would be a data clash if more than one unit echoed the characters. However, echoback is the normal mode of operation for terminals and is useful for debugging purposes. Therefore, there is a special station number – ***zero*** – which will echo-back characters received. No other station will echo-back.

To avoid data clashes when there is a cold re-boot of all units, the default station number is ***255***. Thus, the first action on installing or powering-up a new system would be to set one of the units to station zero.

If the ***attention key*** is held down during a cold-boot or manual reset then the station number is set to 0 instead of 255.

Echoback operation

- character $0A (line feed) is ignored
- character $0D (return) is echoed as $0D, $0A
- character $08 (backspace) is echoed as $08, $20, $08 in order to synthesise a 'left delete' action.
- all other characters are echoed as themselves
- echo-back takes place as the character is copied from the TIB to the CLB, and not when it is received into the TIB.

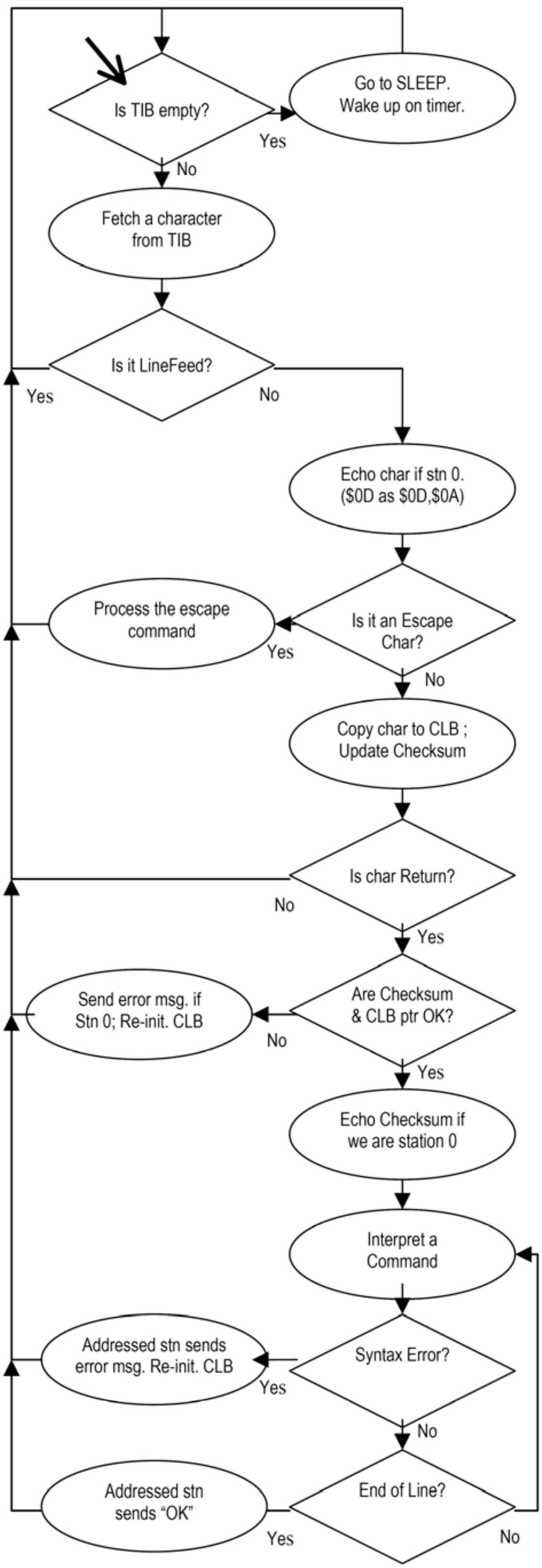

Is TIB empty?
Yes
No
Go to SLEEP.
Wake up on timer.
Fetch a character
from TIB
Is it LineFeed?
Yes
No
Echo char if stn 0.
($0D as $0D,$0A)
Is it an Escape
Char?
Yes
No
Process the escape
command
Copy char to CLB ;
Update Checksum
Is char Return?
No
Yes
Are Checksum
& CLB ptr OK?
No
Yes
Send error msg. if
Stn 0; Re-init. CLB
Echo Checksum if
we are station 0
Interpret a
Command
Syntax Error?
Yes
No
Addressed stn sends
error msg. Re-init. CLB
End of Line?
Yes
No
Addressed stn
sends "OK"

Figure A9-10 : Flow chart to describe character interpretation

Backspace processing has been omitted from this flowchart. It occurs before the test for escape characters

Treatment of Backspace

A simple terminal, operating using echo-back, requires the device that provides the echo-back to process any special characters such as backspace, line scrolling and so on. The only special operation allowed for with this system – and this is mainly for development / debugging purposes – is the handling of a backspace.

When a backspace ($08) is received, it is echoed back as backspace-space-backspace, which is a universally accepted method of achieving a backwards-delete action in a terminal buffer.

In addition, of course, the Command Line Buffer must be suitably processed. This requires a special action where escape characters are involved, as will be discussed below.

<u>Error messages</u>

The interpreter issues a number of diagnostic and error messages. Whether these are transmitted back to the terminal or just discarded depends on various circumstances, the most important of which is whether the unit is being uniquely addressed at the time. For example, if there is a checksum error, we must assume that the station number itself could have been received in error, in which case the unit should not respond with an error message because there could be a data clash.

The line interpreter begins by echoing back the characters received by station zero. Stations other than zero will not echo anything back until the line has been entered in full, its checksum verified and a valid station number received, which matches the station number of the unit. Note that the Global address character will, for this purpose, only match station zero. Possible error messages include

1	Command Line Too Long	Maximum 31 characters including the terminating CR
2	Checksum Error	
3	Number Out of Range	Valid station numbers are 0 to 127. (In fact, this error message is never seen because the interpreter has validated the station number it will not issue error messages)
5	Number Expected	
6	Number Too Large	Numbers must convert to decimal values between 0 and 255
7	Unknown Argument	
8	Unknown Command	

<u>Transmission of characters from the unit</u>

Some commands will ask for data to be returned. A unit will only respond with data if…

- its station number matches the addressed station, or
- it is a global command and the station number is zero.

‘Zoned’ commands, apart from Global commands, are not yet implemented.

The action, if the supplied station number does not match the unit’s address is for the command line to be abandoned. If the unit is station 0 it will issue an error message as noted in §A9.6.2.2. However, global commands always execute, but only station zero will send a response. So, for example, the command **GK** will reset all the keyswitch counters, but only station zero will respond with the contents of the keyswitch counter.

Escape Characters

In general characters are not acted on until the CLB is interpreted. However, there are three ‘escape’ characters that have additional actions.

Clock synchronisation character.
When Received: Resets the real-time clock to zero

Line-loss character. Indicates that line power has been lost. This character is usually generated internally by the unit itself.
When TIB copied to CLB: program enters ***Alarm mode***

Attention character. Indicates that the attention key has been pressed. This character is usually supplied internally by the unit itself.
When TIB copied to CLB: run-time action for this command is executed. (This may be one of several different actions).

For completeness, we can note that in addition to the above actions, when the TIB is copied to the CLB a null character is substituted for the escape character. The null is ignored by the command line interpreter, but its presence acts as a ‘placeholder’ and aids the processing of the backspace character.

Operating Commands

Syntax

station command [command] checksum end-of-line*

where

- *station* is *number* or *global-station-indicator*
- *command* is [space]* *character** [[*space*]* *number*]*
- *number* is *decimal-number* or **#***hex-number*, terminated by a non-numeric character
- *checksum* is *character* | *character-to-force-valid-checksum*
- *end-of-line* is $0D

Interpreting Numbers

At any point where a number is allowed this may be a decimal number, or a hexadecimal number immediately preceded by the hash character, **#**. A future provision for binary numbers is being considered.

Numbers are terminated by any non-numeric character. That is, by any character that does not form a valid numeral in the number base being used at the time.

Numeric strings may be padded with leading zeroes if desired.

After conversion, numbers must be in the range 0 to 255. This is because, at present, there is no need to parse multi-byte values.

Station number
The station number can also be **G** indicating a global command. Zoned commands are not yet implemented.

The range of valid station numbers in the present implementation is 0 to 127.

Note: the cold-boot default is station number 255, therefore the units will only respond to a global command; and this should be the command to set the station numbers.

Command
Commands consist of a string of non-numeric characters. Leading spaces are ignored. The commands will usually be one or two alphabetic characters. For example **VR** might indicate "set visual alarm direction to Left". Whether you consider **VR** to be a command, or **V** to be the command and **R** to be the data is a moot point, which is mostly a matter of customer preference. Internally, the software considers it to be the latter option.

Data
Some commands require data and other syntactical elements. Because of the way the CLB is parsed, there is no necessity for elements to be separated by spaces although, in general spaces are allowed.

Checksum
The final character is a single-character checksum. If this checksum is incorrect, the line will be ignored. If the checksum calculates to be an 'escape' character (see above) then this problem can be avoided by inserting a 'white space' character immediately before it.

<u>Further Notes</u>

Force-Validation Character
Mainly for debugging purposes, there is a special character which, when used as a checksum will always validate the line. This, of course, slightly reduces the worth of the checksum facility and, in future issues of the software, this may be disabled.

Debugging: echo-back of checksum
If station zero is addressed with the "force validation" character, it will echo back the value that the checksum should have taken. This is displayed within square brackets. Checksums are always printable ascii characters.

Calculating and verifying the checksum

- If character is < $20 or >$7F, ignore it. (non-printing characters should not be used, in any case).
- Subtract $20 from each valid character – including the checksum.
- Invert the l.s.b. of each character.
- ex-OR the adjusted characters.
- Invert the l.s.b. of the result
- Add $20 to the result.
- If the result is $21 ("!") then the checksum was correct. If the result is any other value then adding that value to the string will result in a valid checksum.

For example, the string **ABC** produces a checksum of **@**. And the string **ABC@** produces a checksum of 'space'.

The reason for shifting the characters by $20 is to ensure that the checksum is a printable character. The reason for inverting the l.s.b. is to ensure that 'space' can affect the checksum by its inclusion in a string. (see note, above, on how to avoid the checksum being an escape character).

Command List

Command	**Syntax**	**Description**	**Comments**
Return the Temperature Reading	*station* **TR** [n]	Return [n] readings. Default to n=1. N=0 enters infinite loop.	The temperature logger currently makes use of the same digital filter as the CO sensor, so the command **CA** can be used. The autozero is not, however, available, as its setting is over-ridden by the **TR** command.
CO sensor readings See §A9.7.4 below	*station* **CH**	Set range to "high"	Range is –271 to 2023 ppm. This command or the **CL** command must be used after a **TR** command to reset the amplifier's gain and offset. This command sets a default offset that will over-ride any autozero set by the **CA** command.
	Station **CL**	Set range to "low"	Range is –27 to 200 ppm. See notes immediately above.
	Station **CR** [n]	Return [n] readings. Default to n=1. N=0 enters infinite loop.	"Press any key to terminate". (After each line of data is printed the Terminal Input Buffer is examined and, if any characters are present, the command is terminated, and the message "Abort" is printed).
	Station **CT** [n]	Execute a self-test, returning [n] readings. Default to n=1. N=0 enters infinite loop.	As with **CR**, "Press any key to terminate". The duration of the self-test current is set in the CO_selftest register. After the duration of the self-test, the unit will transmit "***" before continuing to supply CO readings for as long as was requested. If n is shorter than the self-test period, the self-test current is removed when the command terminates.
	Station **CA** [n]	Advanced settings: set the **filter_mode** register to n Default to n=0	This is mainly for use during debugging. See notes below. [During further development, command will be expanded into a range of bit-setting commands].
	Station **CA ?**	Query the **filter_mode** register contents	This is for use during debugging.
	Station **CB** [n]	Set the **CO_selftest** register to n seconds. Defaults to hard-programmed value.	
	Station **CB ?**	Query the **CO_selftest** register contents.	
LED Settings	*station* **VL**	Set visual alarm arrow to LEFT	These commands set the **alarm_led_dir** register. Reset to default on cold-start
	station **VR**	Set visual alarm arrow to RIGHT	
	station **VB**	Set visual alarm arrow to BOTH	
	station **VN**	Set visual alarm arrow to NONE	To achieve this, **led_dir** is cleared, rather than the pattern register.
	Station **VA** [n]	Advanced settings: set the visual alarm pattern to n (hex). Defaults to hard-programmed value.	Sets **led_alarm_pattern** Reset to default on cold-start

	station **VD** [n]	Demonstrate visual alarm for n ticks, defaulting to 16. A tick is $1/8^{th}$ s.	The unit currently enters a loop when executing this command so it will not respond to any other commands. The maximum duration of the alarm is 255 ticks (32 s).
	station **VD ?**	Query the **alarm_led_dir** register contents	
Sounder Settings	*station* **AA** [n] [command not yet implemented]	Advanced settings: set the audio alarm pattern to n (hex). Defaults to hard-programmed value.	Sets **audio_alarm_pattern** Reset to default on cold-start. Sounder can be disabled with pattern FF
	station **AT** [n] [command not yet implemented]	Advanced settings: set the sounder "sound-type" to n (hex). Defaults to hard-programmed value.	Reset to default on cold-start
	station **AD** n [command not yet implemented]	Demonstrate audio alarm for n ticks, defaulting to 16. A tick is $1/8^{th}$ s.	The unit currently enters a loop when executing this command so it will not respond to any other commands. The maximum duration of the alarm is 255 ticks (32 s).
Beacon Settings	*station* **BA** [n] [command not yet implemented]	Advanced settings: set the beacon alarm pattern to n. Defaults to hard-programmed value.	Sets **beacon_alarm_pattern** Reset to default on cold-start. Sounder can be disabled with pattern FF
	station **BD** [n] [command not yet implemented]	Demonstrate beacon alarm for n ticks, defaulting to 16. A tick is $1/8^{th}$ s.	The unit currently enters a loop when executing this command so it will not respond to any other commands. The maximum duration of the alarm is 255 ticks (32 s).
Attention Switch	*station* **K**	Read the attention switch register and clear it.	
Alarm Settings	*station* **ZT** [n] [command not yet implemented]	Set alarm time-out before 'sustained' state. Defaults to hard-programmed value.	Reset to default on cold-start
	Station **ZA** [n] [command not yet implemented]	Advanced settings: set the alarm pattern for timed-out state to n. Defaults to hard-programmed value.	Reset to default on cold-start
Clock Skew commands. See §A9.7.5 below	*station* **SS** [n]	Set the size of the skew step. This is used in the **SK** command.	Set **skewStepSize** Reset to default of 8 on cold-start
	station **SS ?**	Query the **skewStepSize** register contents.	
	station **SK** [n]	Set the alarm 'skew'. n is in units of $1/128^{th}$ s. Defaults to n = **skewStepSize** * *station*	Sets the **skew** register. Note: specifying a value of n=0 is the same as omitting n (i.e. the default action is undertaken) so setting a zero skew is not possible. See notes below. Reset to default of 0 on cold-start
	station **SK ?**	Query the **skew** register contents.	
Address-setting commands	*station* **SA** [n1] [n2]	Set *station* to address n1 (default 0). Set the clock skew to n2 (default 0). The clock skew is set as described under command **SK**. If *station* is Global then the action is deferred until the attention switch is pressed.	Repeated **G SA** commands can be used to set the addresses on an installed system. It is, however, vital that the procedure ends with a final **G SC** command.

	station **SC**	Cancel a previous **G SA** command.	
Escape Commands	**^**	Reset Clock, allowing for skew.	
	@	Loss of Line	
	!	Attention button pressed	
Other Syntactical Elements	**G**	Character to indicate global address	
	#	Operator to indicate hexadecimal number	
	. [point]	Character to force a valid checksum	
Specialist Commands	[command not yet implemented]	Set FSK front/back porches	Reset to default on cold-start
	[command not yet implemented]	Set bit-rate	Reset to default on cold-start
	station **"***string*	Echo a string. Terminate with " or end-of-line	for debugging
	station **%***number*	Echo a number	for debugging
	station **XD**	Execute a Watchdog reset	The addressed station prints the message "looping…" and enters a tight loop, which forces the watchdog timer to trip. When this happens the unit re-boots and prints a warm start message. Most registers are initialised during a warm re-boot, apart from a few specified user-variables that includes, for example, the station number.
	station **XC** [n]	Alarm Inhibit: Ignore line loss if n is 0xFF. Default n=0.	See §A9.4.2.3 for a description.
	station **XS**	Print a status message	Currently, this command has no action, and terminates with the *nnn*:ok message.
	station **XF** [n]	Don't disable FSK transmitter for station 0 if n is 0xFF. Default n=0.	For debugging use: Station 0 can be instructed to not disable the FSK after transmitting. This specialist operation must be cancelled when there are multiple units on the line.
	Hardware Reset	Execute a MCLR pin reset	During this cold-start, all registers are initialised, including the user variables. The unit prints "Reset", followed by "Hello from Station nnn". The unit powers up as station 255 unless the attention key is held down during the reset, in which case it powers up as station 0 (the echo-back station).

CO Sensor – Advanced Settings

The **filter_mode** register contains the following bit flags

0 **Force zero.** Setting this bit forces all subsequent ADC samples to be read as zero.

1 **Force full-scale.** Setting this bit forces all subsequent ADC samples to be read as 'full scale'. The 10-bit ADC is left justified, so these are read as 0xFFC0.

2 **Enable Digital Filter.** Setting this bit enables the digital filter, which has a time constant of 32s.

3 **Not Used**

4 **Kick-Start Filter**. Setting this bit causes the digital filter's accumulator register to be set to the value of the next ADC sample. The flag is then cleared.

5 **Auto-zero**. Setting this bit causes the next ADC sample to be stored in the **offset** register and used to modify all subsequent readings. The flag is cleared after use. The offset register is set to the system default after a cold or warm reboot (i.e. after a system reset or a watchdog reset, which occurs when line power is restored). ***Warnings:*** the value of the offset register cannot currently be read back, so it is important to keep track of when it has been reset to the system default. The auto-zero function is probably best used with the digital filter enabled, but only after it has had time to fully stabilise – 10 time constants is five minutes.

Clock Skew and Address Setting Commands

In order to obtain 'running light' effects, it is possible to delay or 'skew' the internal system clock, so that each outstation is running in a slightly different 'time zone' for want of a better phrase. Since the flashing LED patterns are synchronised to the internal real-time clock registers, this allows the flashing to be delayed from one unit to another. The 8-bit clock **skew** register holds the skew in steps of 1/128th s. The **skew** register can be set to a specified number, or to a number that is related to the station number. The command **G SS 8 SK** will set the skew to 8 times the station number, on all stations.

The effect of the **skew** register is only applied to the real-time clock when the 'synchronise' command, **^** is sent.

The skew can be set separately to the station address although, for convenience, the 'set address' command allows both to be set together.

The 'set address' command **SA** has immediate effect when it is specified for a single station, but you must take care that you do not re-allocate a station's address to one that is already in use. When a global address is used, the **G SA** command stores the station number and skew value and they are only applied when the attention switch is pressed. Thus a series of **G SA** commands can be used to initialise an entire system. The deferred action of the **G SA** command is cancelled by the **G SC** command, which must, of course, be a global command.

When the address of a unit is altered, it sends a message "Hello from Station *nnn*" and then enters a forced loop, exactly as if the **D** command had been executed.

Example of Dialogue

In this brief example the text typed by the operator at a 'dumb' terminal user is in ***bold italic***.

User Action	Reason	Terminal Screen
Press Reset Button:	To initiate a cold start	`Cold Start`
		`Hello from Station 255`
GSA0. ↵	To prepare to set address to zero	
Press Attention button	To set this unit's address to zero	`Hello from Station 0`
0CR5. ↵	To report five CO readings	***0CR5.***
	Unit responds with checksum	`[5]`
		`[1EC0]     0.5ppmCO`
		`[1F00]     0.7ppmCO`

		`[1F00]     0.7ppmCO`
		`[1F00]     0.7ppmCO`
		`[1F00]     0.7ppmCO`
	Unit responds with “ok”	`0:ok`
0VD100. ↵	To blink LEDs	***0VD100.***
	Unit responds with checksum	`[2]`
	Unit responds with “ok”	`0:ok`
GVRC↵	To set LEDs Right, globally, using checksum	***GVRC***
	Unit responds with “ok”	`0:ok`
GSA.↵	To prepare to set address to 45	***GSA45.***
		`[T]`
		`0:ok`
Press Attention button	To set this unit’s address to 45	`!Hello from Station 45`
45CR. ↵	To report a CO reading (no echoback)	
	Unit responds	`[1F00]     0.7ppmCO`
	Unit responds	`45:ok`
32CR. ↵	Unit doesn’t respond	

Design Modifications

There are a number of design changes that are currently under consideration. The will form the next stage of development.

Beacon Hardware

A current drain path has been identified that is active when the battery is isolated by removing the **off** link (see description in §A9.3.7. This reduces the battery life when the units are in storage.

When the battery voltage falls low enough to trip the Reset line, the MCU will wake from sleep and start running at full current, waiting for the Reset to be resolved. This will accelerate the discharge of the battery. Some further design work is required to cure this problem.

The tolerance on the FSK oscillator components is such that a ‘select on test’ procedure must be used to fix the frequencies. This can be avoided by a re-design of the FSK oscillator.

Some ‘design verification’ of the brownout circuit needs to be performed, in order to optimise the voltage thresholds.

Beacon Software

There are a few software bugs that remain to be corrected, and some features that are not yet implemented

Control Unit Hardware

The synchroniser circuit on the Control Unit could be replaced by a software module, using a PIC chip, that would allow an increased data rate, and would allow us to investigate other modulation methods, e.g. Manchester code and various types of BPSK.

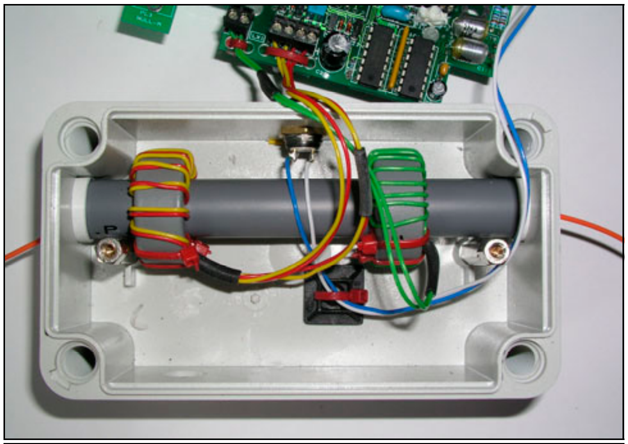
Graphical User Interface

Development of a GUI is a necessary adjunct to this project.

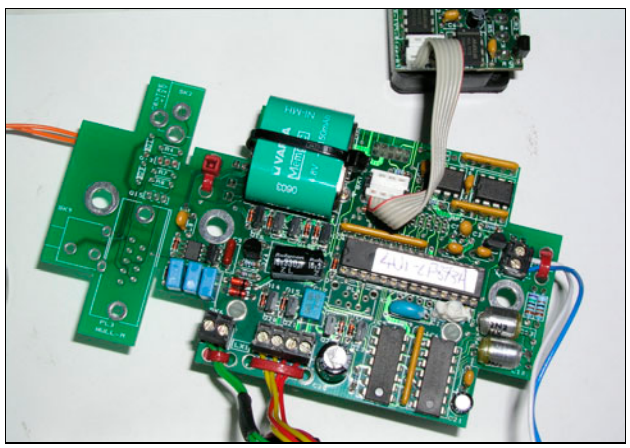
Assembly Diagrams

The diagrams on the next few pages give some indication of how the UPTUN beacons are assembled.

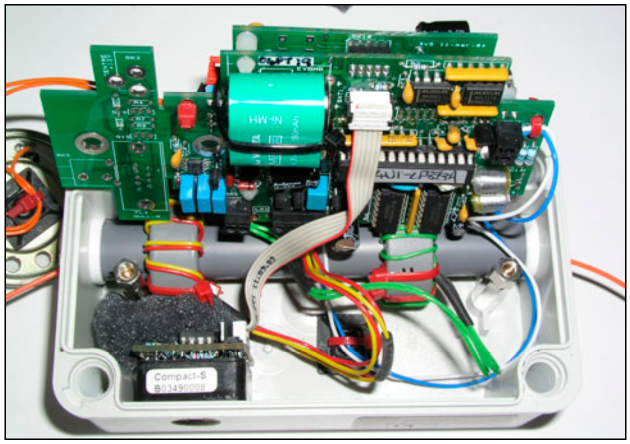
Outstations



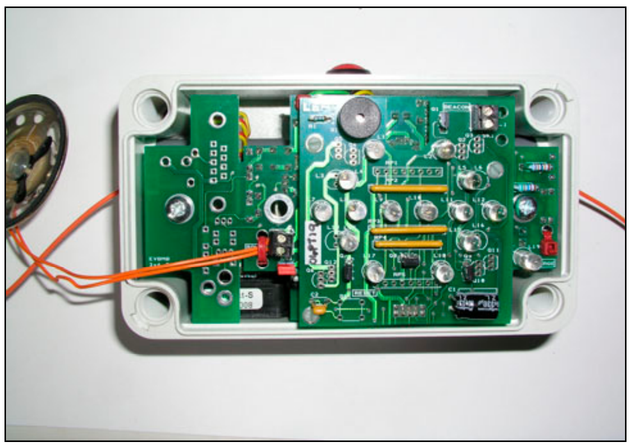
Toroids are fitted to plastic tube and wired to circuit board. Note colour coding of wires. Attention switch is mounted; wires secured to bottom of box for strain relief



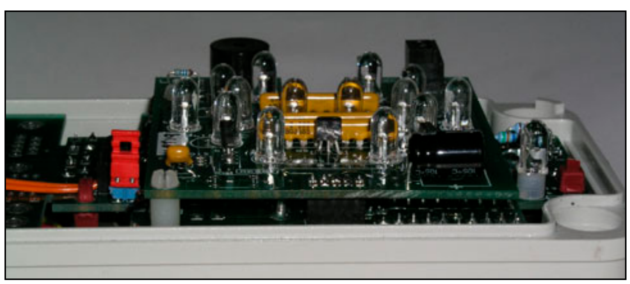
Battery is plugged into on-board sockets and is secured with cable-tie. Wires to toroids, sounder and attention switch secured to board with cable tie. Carbon monoxide sensor sub-assembly plugged into board



CO Sensor fits into hole drilled in enclosure. It is secured in place (in these engineering samples) with a wad of cushioning foam



PCB fixed to mounting pillars. Wayfinding LEDs are on a sub-assembly that plugs into the main PCB



Close-up of LED sub-assembly showing plug/socket and fixing pillars. The red programmable link to the left is the battery isolator

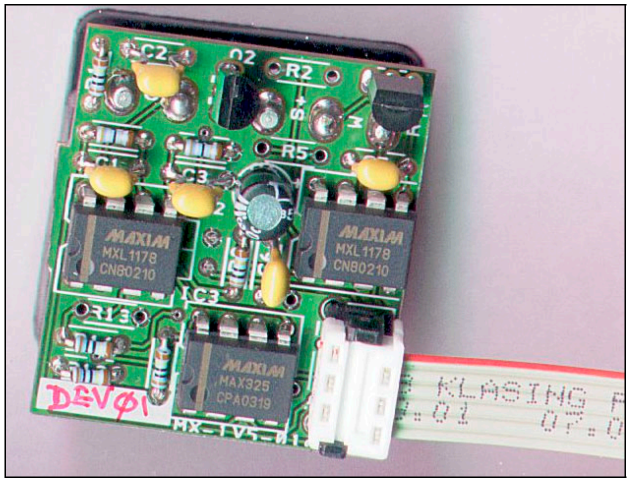
Sounder is held in place with foam padding. When assembled, it presses tightly against lid of box

Completed assembly

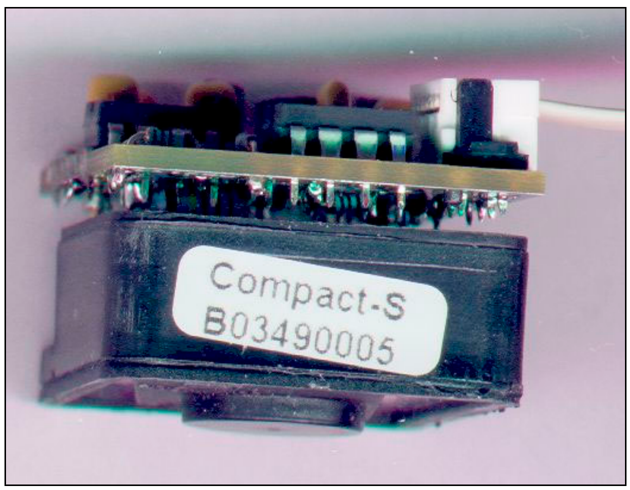
Figure A9-11 : Photos showing assembly procedure for UPTUN beacon

CO Sensor

The CO Sensor plugs into a signal conditioning board sub-assembly. This board has components on both sides (but is not a surface-mount assembly) and has ground planes to help to reduce noise and interference.



View of CO Sensor signal conditioning board



Completed assembly

Figure A9-12 : Photographs of CO Sensor sub-assembly

Control Unit

The Control Unit is still in a development phase. This photograph shows the laboratory prototype.

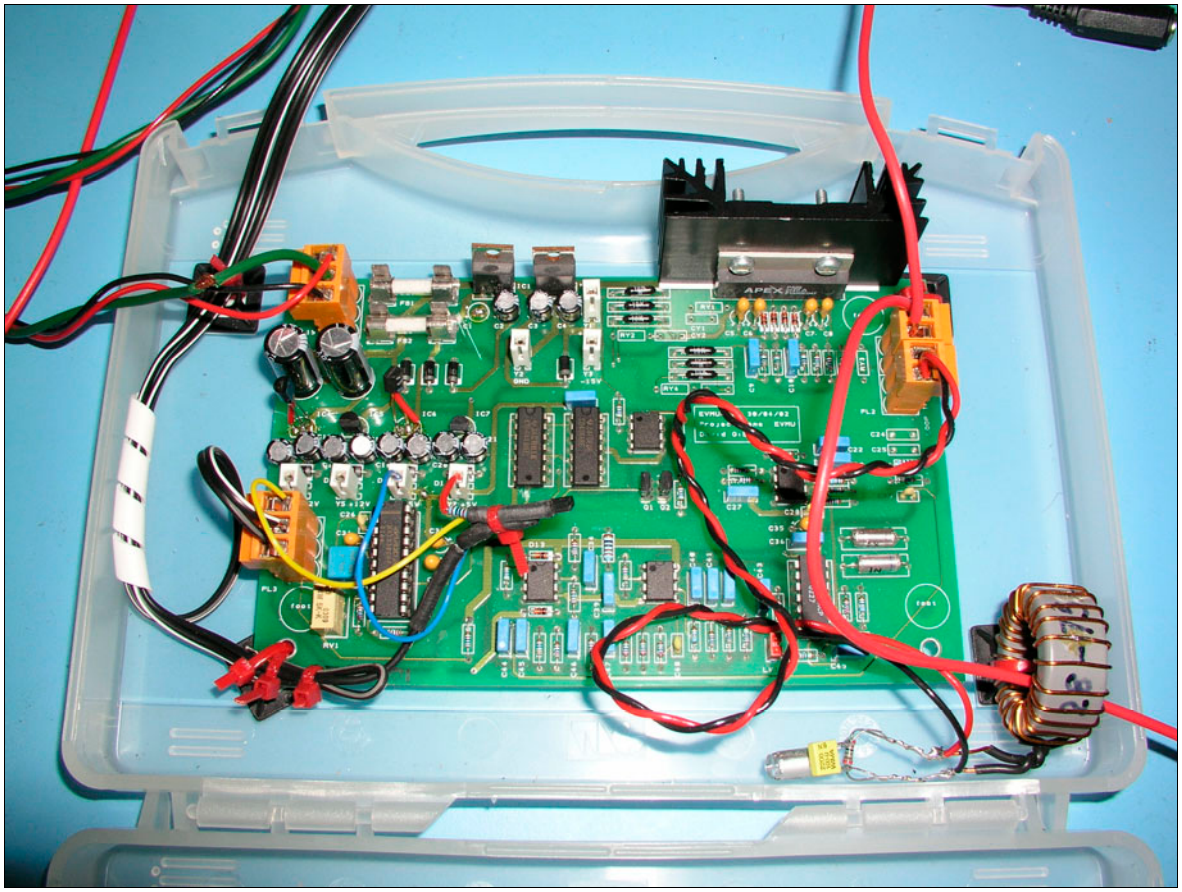


Figure A9-13 : Photograph of Control Unit PCB. This is the ‘lab’ prototype.