Effective Firefighting Operations in Road Tunnels

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SP Technical Research Institute of Sweden

Fire Technology

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The photo on the front page was provided by Anders Bergqvist at the Greater Stockholm Fire Brigade.

Abstract

The main purpose of this study is to develop operational procedures for fire brigades in road tunnels. Although much progress has been achieved in various fields of fire safety in tunnels, very little attention has been paid specifically to fire fighting in tunnels. This study is focused on obtaining more information concerning how effectively the fire brigade can fight road tunnel fires and what limitations and threats fire brigades may be faced with. This knowledge can help parties involved in tunnel safety to understand safety issues and enhance the level of fire safety in road tunnels.

The report is divided into three main parts. The first part consists of a review of relevant studies and experiments concerning various key parameters for fire safety and emergency procedures. The history of road tunnel fires is then summarised and analyzed. Among all road tunnel fires, three catastrophic tunnel fires are highlighted, focusing on the activities of fire brigades and the operation of technical fire safety facilities. In the second part specific firefighting operations are developed. This has been based on previous experience and new findings from experiments performed in the study. In the last part, information is given on how the proposed firefighting operations can be applied to the management of fire safety for road tunnels. Two proposals are developed and presented: fire scenarios for firefighting strategies and tunnel classification models for risk management for fire brigades.

Key words: Road tunnel, Firefighting operations, Offensive (Defensive) strategy, firefighting tactics.

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Preface

This study has been sponsored by the Korean Government Long-Term Fellowship Program. This Fellowship is aimed at providing advanced training for middle officials of the Korean Government by sending them abroad for two years of post-graduate study. Hak Kuen Kim, one of the authors of this report, has worked as a fire officer for 10 years in Korea. In 2006, he was selected to receive this fellowship and the work presented in this report is a part of Hak Kuen Kim's research during his stay at SP. This research was carried out together with the co-authors Anders Lönnermark and Haukur Ingason at SP Technical Research Institute of Sweden.

The authors want to acknowledge Anders Bergqvist at the Stockholm Fire Brigade for his contribution to this work. His sound advice and ideas have been very valuable for this work. Without his novel ideas concerning how to fight fires in tunnels, this work would not have been possible.

Nomenclature

ATMB	Autorout et Tunnel du Mont Blanc
BA	Breathing Apparatus
CCTV	Closed-Circuit Television
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
SITMB	Societa Italiana del Traforo di Monto Bianco

1 Introduction

Continuous efforts are being made to increase the level of safety of tunnels worldwide. A number of experiments, using real or simulated vehicles, have been carried out and a range of safety aspects for road tunnels have been examined. Much progress has been made but there is still much work to do in this field.

Although much progress has been achieved in various fields of safety in tunnels, it appears that less interest has been paid to the operations of the fire services. One of the main reasons may be that the planning work for firefighting and rescue operations is usually carried out exclusively by fire authorities and it is difficult for civilians to obtain insight into the aims and capacity of each individual fire brigade. The fire and rescue authorities participate in all processes related to safety in tunnels and play an important role in each planning stage. Thus, it is natural that the work of fire brigades should be discussed and evaluated as an integrated part of the tunnel's overall safety concept. Safety cannot be achieved by efforts from only one or two disciplines but requires a multi-disciplinary approach.

The main focus of this study was to develop operational procedures for fire brigades. Further, attempts were made to obtain some useful information on how effectively fire brigades respond to fires in road tunnels and what limitations and threats fire brigades can be faced with. This information will assist all parties involved in tunnel safety to understand safety issues in tunnels thereby enhancing the level of fire safety in road tunnels.

This study deals with fire brigade operations in road tunnels. Operations in rail tunnels should be handled in other ways. Unless commented otherwise, "tunnels" refers only to road tunnels in this report and the term "fire operations" includes activities such as: extinguishing fires, rescuing fire victims and other related actions which fire brigade performs to remove potential danger for lives and property in tunnels relating to fires.

This report contains three different parts. In the first part, previous studies on the firefighting operations and experiments on various aspects of fire safety of road tunnels are reviewed. Two related studies are identified and their conclusions are summarized. Also, the history of road tunnel fires is analyzed. Among all road tunnel fires, three catastrophic tunnel fires are highlighted, focusing on the activities of fire brigade and operation of fire safety facilities. In the second part, specific firefighting operations are developed, based on the previous experience and new findings from an experiment carried out for this study. Finally, in what way the proposed firefighting operations can be applied to the management of fire safety for road tunnels is described. In this context, two proposals are developed and shown: fire scenarios for firefighting strategies and tunnel classification models for operations of fire brigade.

2 Background

2.1 Previous studies

Very little discussion of the operations of fire brigades in tunnels can be found in the literature. Two main studies that have a close link to this research have been identified. They are briefly summarised below.

2.1.1 What can the fire brigade do about catastrophic tunnel fires?

In the early part of a report by Ingason et al. [1] and Bergqvist [2] general background such as concepts of tactics and firefighting operations are briefly introduced. Methods available for the fire brigades to fight a tunnel fire and basic requirements, which should be considered when they are incorporated into working methods, are addressed.

The highlight of the work is the proposal of a few tactical models applicable to the different geometries of a tunnel and different traffic features, i.e., single or double bore tunnels and heavy or light traffic. As the working methods are illustrated in drawings like Figure 2.1 – Figure 2.5, they can be better understood. The concept of the tactics suggested by Ingason et al. and Bergqvist can be summarized as follow:

- **Tackling fires in twin-bore tunnels**
  - All traffic not directly related to the firefighting activity must be stopped. The fire brigade approach should be made from the unaffected bore of the tunnel. First responders should start to tackle the vehicle fire. At the same time, the upstream side, i.e. the smoke-free zone, should be evacuated. The second and third crews to arrive should either assist the first crew, or extinguish the fire on the downstream side or search the tunnel for trapped tunnel occupants, see Figure 2.1.

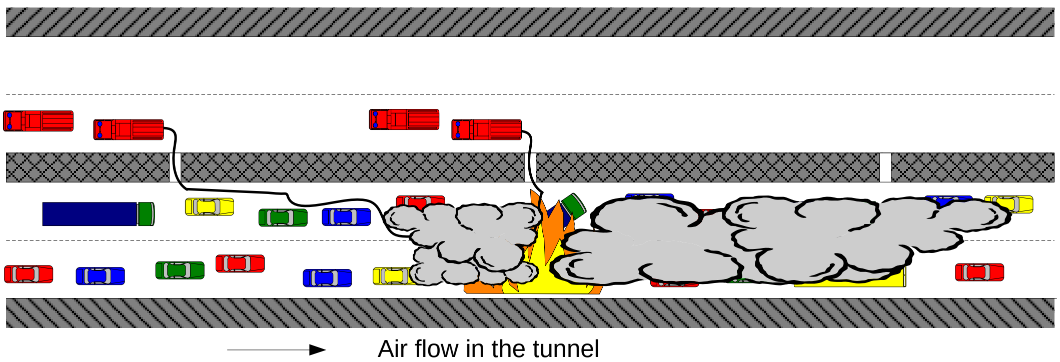


Figure 2.1 Tackling a vehicle fire in a twin-bore tunnel with no queuing traffic under the smoke.

  - If the tunnel is located in an urban area, it is likely that the vehicles on the downstream side may have difficulty in escaping out of the tunnel when the smoke spreads to their location. In that case additional operations should be included in the tactics following the activities proposed above, see Figure 2.2.
  - The ventilation rate should be increased after extinguishing the fire. If the fire is not under control, the direction of air flow should be reversed to

vent out the smoke, which may help trapped occupants on the downstream side, see Figure 2.3.

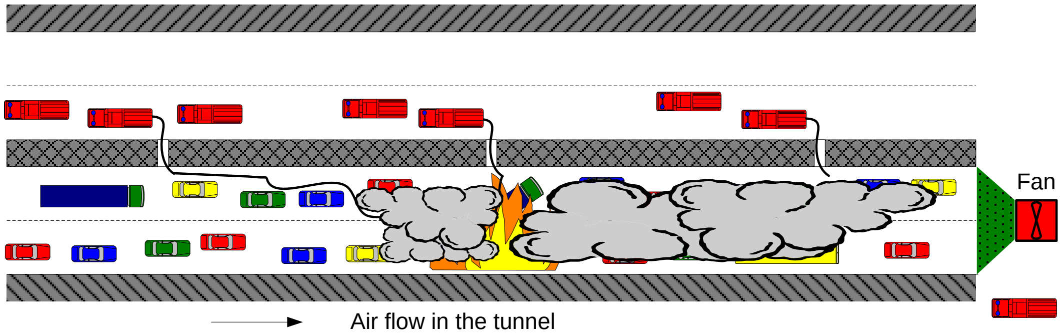


Figure 2.2 **Fire and rescue operations dealing with a car fire in a twin-bore tunnel with queuing vehicles under the smoke.**

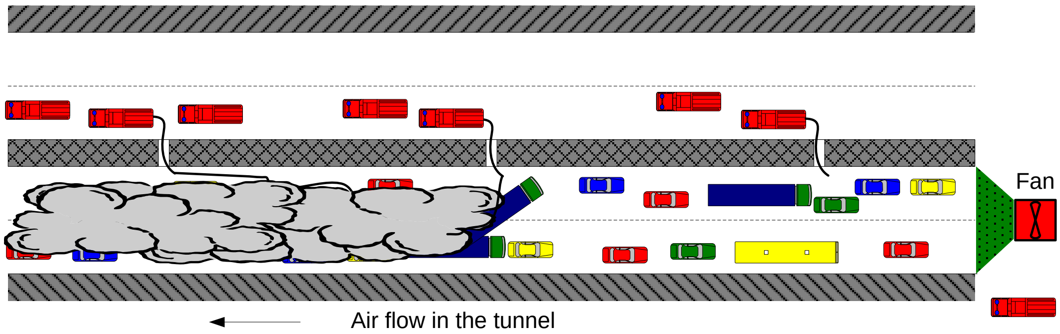


Figure 2.3 **Fire and rescue operation dealing with a car fire in a twin-bore tunnel queuing traffic, after reversal of the direction of air flow.**

- **Tackling fires in single-bore tunnels**
  - One should first assess the situation and ensure that the direction of air flow is in the most desired way. The responders first on the scene should try to attack the fire. If this is not possible they should retreat to leave space for evacuation operations. The occupants upstream of the fire should be evacuated. Simultaneously, access from downstream should be facilitated for rescuing person trapped close to the tunnel mouth, see Figure 2.4. Once the fire has been extinguished, the smoke is vented out of the tunnel. If it is impossible to suppress the fire, the direction of air flow should be reversed in order to save those evacuating in the smoke on the original downstream side. Of course, before the ventilation is reversed, search and rescue must be completed on the upstream side, see Figure 2.5.

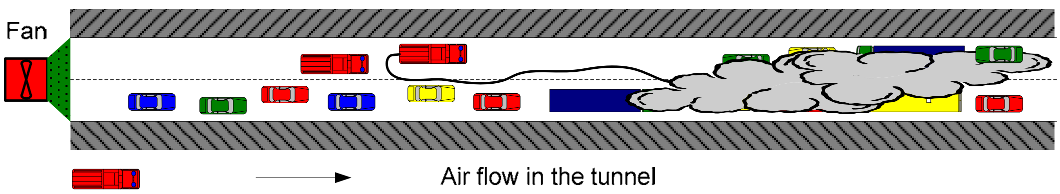


Figure 2.4 **Tackling a car fire in a single-bore tunnel.**

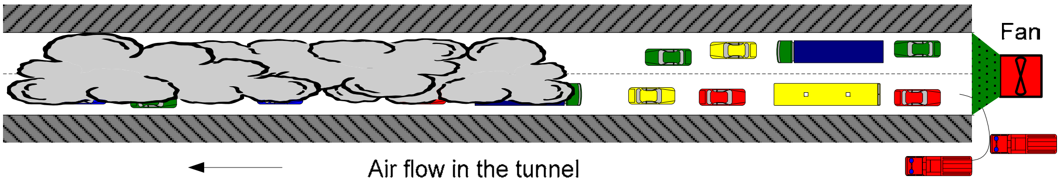


Figure 2.5 Fire and rescue operation dealing with a car fire in a single-bore tunnel after reversing the direction of air flow.

Some experimental data was introduced by Ingason et al. [1] and Bergqvist [2] to illustrate problems and difficulties with which fire brigades may be faced. These include: calculations of air flow reversal, movement speed and range of breathing apparatus groups, absolute minimum water requirements and maximum throw length of firefighting nozzles in a tunnel environment.

The authors of these reports [1, 2] state that the fire brigades should be able to reach the fire scene and start work within 10 minutes after fire alarm, pointing out that vehicle fires appear to rise rapidly after about the first 5-10 minutes. Finally, Ingason et al. and Bergqvist emphasized the necessity of more research on working methods or tactics especially in relation to assess to the incident, the use of breathing apparatus and the protection of firefighters.

2.1.2 Fire and rescue operations in tunnel fires: a discussion of some practical issues

The study by Bergqvist et al. [3] presents various aspects of fire and rescue operations performed by fire brigades in a fictitious tunnel fire incident in a train carrying approximately 240 people. The result of the analysis can be applied to the case of road tunnels although the scenario considered by Bergqvist et al. [3] is a fire occurring in a rail tunnel.

The descriptions of foreseen situations which firemen may encounter are based on information coming from investigations, tests and the author's experience. Such situations are related to limitations in the fire services' resources and critical information and the effect of this on decisions of proper tactics. This is put in relation to each stage of the fire response, for example fire alarm, mobilization, arriving and access to the scene and rescue and attack of fire,. In addition, in-depth research has been made on several main problems in dealing with a fire and rescue situations in a tunnel. The foreseen situations and proposed solutions mentioned in the paper can be summarized as follow [3]:

- Difficulty to obtain an overview of the incident site
  → <u>Proposed solutions:</u> Various forms of monitoring and surveillance equipment (assists the fire brigades to assess the incident)
- An extensive evacuation/life-saving situation
  → <u>Proposed solutions:</u> 1) Training, rehearsals and proper theoretical education of the fire brigade prior to the incident (facilitate dealing with huge number of evacuators). 2) Well-designed emergency exits and improved methods for using the ventilation systems and breathing apparatus (facilitate and assist evacuation).
- Dealing with noxious fire gases
  → <u>Proposed solutions:</u> 1) Proper observation of the movement of the smoke throughout the incident operations. 2) Proper preparation and planning of ventilation and fire gas control.
- Difficulty to assess the risks faced by fire and rescue personnel

→ Proposed solutions: 1) Well-trained incident commanders with specific instructions concerning such incidents in advance. 2) Support for performing better risk assessments, e.g. checklists or outline plans.

- Difficulty to reach the fire

→ Proposed solutions: 1) Improved working procedures and equipment, especially breathing equipment. 2) Better and more effective guidance and location system, visibility and smoke toxicity information.

- Control of the fire gases

→ Proposed solutions: Further, in-depth research into effective search, rescue, firefighting and assistance of evacuees in connection with use of ventilation systems.

- Communication between firefighters

→ Proposed solutions: Improved radio communications and mobile systems for extending communication especially for the sake of the breathing apparatus crews.

- Getting water to the site of the fire

→ Proposed solutions: 1) Installation of a permanent hydrant system. 2) Development of improved procedures for running out hoses.

- Extinguishing the fire in the desired manner

→ Proposed solutions: 1) Installation of some physical protection systems, e.g., water spray extinguishing systems. 2) Installation of early detection systems.

In the latter part of the study by Bergqvist et al. [3], a proposal for a model form of tackling fires in single-bore tunnels is provided. The proposal suggests that the first approach should be made from the smoke-free end of tunnel. The work of collecting information for understanding the situations is crucial. Fans can be used to improve the working conditions and safety of firefighters. If the resources are available, breathing apparatus groups could be send to the smoke-filled side of the tunnel. This is done in order to facilitate the evacuation of people trapped in the tunnel. When the work from the smoke-free part has been finished or is no longer possible, the direction of air flow should be reversed and the fire should be approached from the original downstream side and extinguishing operations begun.

In conclusion, the need for further research is emphasized in particular into: what types and sizes of fires can be handled by the fire brigade, how breathing apparatus groups, fire-fighting and ventilation work should be coordinated systematically and how various attack concepts should be investigated for different geometries of tunnels. Lastly, Bergqvist et al. [3] ended by suggesting that the model developed needs to be verified to confirm its applicability in a real incident.

2.2 Further research

It appears that basic outlines of fire operations in tunnels have been illustrated in the previous work described above and these can constitute a sound basis for further research. Now, it is necessary to advance based on these studies so that a greater understanding of the nature of fires in tunnels can be developed.

In the following chapters, a history of tunnel fires is reviewed and discussed, focusing on three major tunnel fires. The aim is to explore the characteristic behaviour of tunnel fires. Further, various findings from experiments and studies have been reviewed, which can provide a theoretical background for development of fire brigade operations.

3 A history of fires in road tunnels

In this chapter, previous tunnel fires are collated and analyzed to obtain an overview of tunnel fires. Further, three catastrophic fires are highlighted from which useful lessons can be obtained for the development of fire brigade operations. In order to do so, the use of fire safety equipment and activities of fire services, were analysed for these fires.

3.1 Fires in road tunnels

Details on fires in road tunnels since 1949 were collected from various publications and internet web sites [4-6]. Although small-scale fires and old incidents have not been described in detail, a total of 69 fire incidents have been compiled [4-6]. All details of fires are presented in Appendix 1. Descriptions of 20 firefighting activities in road tunnels are summarized in Table 3.1.

Table 3.1 Firefighting activities in road tunnels. A more comprehensive list is given in Appendix 1.

Year	Name Country Length (km)	Vehicle where fire occurred	Most possible cause or location of fire	Type of incident	Firefighting
2005	Frejus France/ Italy (12.9)	An HGV carrying tyres	Engine fire	Single fire. Fire spread.	Fire extinguished before it reached glue load in 4th lorry.
2004	Frejus France/ Italy (12.9)	An HGV	Braking system	Single fire	The fire was extinguished easily
2003	Fløyfjell Norway (3.1)	A car	Collision with wall and fire	Collision (wall) and fire. No fire spread.	Fire brigade arrived after 6 min and quickly extinguished the car fire.
	Locica Slovenia (0.8)	An HGV carring a cargo of aluminium beams	-	Single fire	The fire brigade extinguished the fire on arrival.
2002	Tauern Austria (6.4)	A lorry	A faulty engine	Single fire	The fire brigade was able to bring the fire under control very quickly
2001	Gleinalm (7 August) Austria (8.3)	A car	Front collision between a lorry and a car	Collision and fire. No Fire spread.	The fire was successfully extinguished by the fire brigade shortly
	St. Gotthard Switzerland (16.9)	2 HGVs, one carrying a load of rubber tyres	A head on collision between 2 lorries.	Collision and fire. Fuel spill. Fire spread.	The first response fire brigade could not extinguish the fire on early stage.

Year	Name Country Length (km)	Vehicle where fire occurred	Most possible cause or location of fire	Type of incident	Firefighting
	Tauern Austria (6.4)	2 cars	A head on collision	Collision and fire. No fire spread.	The fire was extinguished quickly by the driver of one of the cars
2000	Laerdal Norway (24.5)	A bus transporting about 50 passengers	-	Single fire	The fire was small and was easily dealt with by the bus driver
2000	Saukopf Germany (2.7)	A car	-	Single fire	The fire brigade extinguished the fire easily
	Cross-harbour Hong Kong	A car	-	Single fire	The first emergency response arrived within 3 minutes. But they were unable to control fire. The fire brigade arrived 2 minutes later.
	Tauern Austria (6.4)	An HGV	-	Single fire	This fire was dealt with rapidly and was extinguished within half an hour by firefighters on both sides of the vehicle
1999	Candid Germany (0.252)	A car	Engine compartment	Single fire	Due to the volume of traffic, the fire brigade took a long time to reach the fire, but on arrival the fire was quickly extinguished
	Tauern Austria (6.4)	A lorry with a cargo of spray cans including paints	Front-rear-collision between 4 cars and 2 lorries	Collision and fire. Fuel spill. Fire spread.	The fully developed fire could not be extinguished until substantial long time.
	Mont Blanc France/ Italy (11.6)	A lorry with flour and margarine	Diesel fuel leaking onto hot surfaces of engine compartment	Oil leakage and fire. Fire spread.	The first response fire brigade could not even approach to the fire.
1990	Mont Blanc France/ Italy (11.6)	An HGV with 20 tons cotton	Motor	Single fire	The French firefighters arrived within 10 minutes. Despite the fact that the fire had spread to involve the entire vehicle by this point, the firefighters were able to control the blaze and extinguish it.

Year	Name Country Length (km)	Vehicle where fire occurred	Most possible cause or location of fire	Type of incident	Firefighting
1988	Mont Blanc France/Italy (11.6)	An HGV	-	Single fire	The French firefighters were able to extinguish the fire on arrival
1986	Herzogberg Austria (2)	An HGV	Brakes overheating	Single fire	Although the fire brigade took over 20 minutes to arrive, the fire was extinguished quickly.
1976	San Bernardino Switzerland (6.6)	A bus carring 33 passengers	Engine room overheating	Single fire	Rescue operation started 4 min after the alarm. The fire brigade response was very fast, and the fire did not spread.
1974	Mont Blanc France/ Italy (11.6)	A lorry	Motor	Single fire	The French fire brigade was quick to arrive on the scene and despite thick smoke, was able to extinguish the fire quickly

The fires can be divided into two categories. One category is fire incidents which involve only one vehicle without any involvement or influence from other vehicles at ignition. The list of tunnel incidents shows that these kinds of fires develop relatively slowly if there is no other special factor which may accelerate the progress, such as fuel leakage or explosion of cargo. They are initially small and show some sign of fire, such as smoke and flames, so neighbouring vehicles can see what is happening and prepare for the emergency within a reasonable time. The other category is fire incidents which involve more than one vehicle at the start of the fire and occur as a result of traffic incidents such as a collision between vehicles or between a vehicle and the wall of the tunnel. These kinds of fires are expected to occur suddenly without any previous signs so they may cause panic in tunnel users and have the potential to develop into a catastrophic fire. In this study, the former category is named “Single fires” and the latter “Collision fires”. Among the 69 fires in road tunnels that were analysed, 48 (69.6 %) were single fires and 21 (30. 4 %) cases were collision fires.

The two categories can be divided into sub-categories depending on whether the fire spreads or not. In this study, fire spread means that the fires propagated to another vehicle which is not engaged in the initial fire. The definition of each incident category is:

- **Incident Category 1 (IC1)**: single fire that does not spread to other vehicles.
- **Incident Category 2 (IC2)**: single fire that propagates to neighbouring vehicles.
- **Incident Category 3 (IC3)**: collision fire that is limited to the vehicles which are involved in the collision.
- **Incident Category 4 (IC4)**: collision fire that spreads to other vehicles which are not involved in the collision.

The reason for focusing on the fire spread is that it is one of the key factors determining the consequences of fires. The spread of fire increases the intensity and size of the fire and hampers the operations of the fire brigade. It also involves more vehicles and tunnel users so it can potentially claim many casualties and economic losses. One of the responsibilities of fire brigades is to limit the initial fire to its vehicle of origin, i.e., to prevent the fire from spreading. If a fire does not spread to neighbouring vehicles, the size or the intensity of the fire will be limited and the current firefighting resources and operational procedures fire brigades employ are typically sufficient to tackle the incident. On this occasion, it is not necessary to develop new operational tactics for tunnels. A comparison for each category is presented in Table 3.2.

Forty three fires of Incident Category 1 (**IC1)** are documented. Of these, 25 fires occurred in HGVs (Heavy Goods Vehicles), three fires in passenger cars, 14 in buses or coaches and one in a mobile crane. Among 48 single fires, fire spread is found in only 5 cases. Interestingly, all **IC2** fires originated from HGVs. These were either a petrol truck or lorries carrying a great quantity of combustible goods, e.g. tyres in the Frejus tunnel fire of 2005, 9 tons of margarine and 12 tons of flour in the Mont Blanc tunnel fire of 1999, 600 polystyrene boxes in the Suzaka tunnel fire of 1967, hazardous material in the Salang tunnel fire of 1982, and 11 tons of carbon disulphate in the Holland tunnel fire of 1945. It is reported that most of these five fires have unique factors which may have sped-up the progress of the fire, i.e. oil leakage (Mont Blanc tunnel, 1999), inadequate operational procedures (Suzaka tunnel, 1967) and explosion (Salang tunnel, 1982 and Holland tunnel, 1945). All **IC2**fires claimed casualties and caused significant damage of vehicles.

Seven fires in **IC3** are summarized in Table 3.2. Two cases were related to HGVs: HGV+bus and HGV+car but no cases with HGV+HGV. The other five cases were collisions between vehicles such as cars, buses and motorcycles and the wall of the tunnel (see Table 3.1). Human fatalities occurred in five cases. It is not clear whether human losses were caused by the collision or the fire. However, the likelihood of death or injury in **IC3** fires is very high.

Among 21 collision fires, 13 fires in **IC4** are reported. In all 13 cases, more than one HGV was engaged in the collision incidents. All **IC4** fires started in HGVs or in the vehicles which collided with HGVs. Casualties happened in all **IC4** fires either due to the fires or the collisions. Collisions between car(s) and bus(es) and subsequent fires were not reported at all.

Table 3.2 Analysis on the previous fires in road tunnels.

Type (%)	Category	No. of fire (%)	Location of original fire	Casualties
Single fire[a)] (69.6 %)	**IC1**	43 (62.3 %)	HGV: 25 Bus or coach: 14 Passenger car: 3 Mobile crane: 1	Casualty: 11 No casualty: 32
	IC2	5 (7.3 %)	HGV 5	In all fires, casualties occurred
Collision fire (30.4 %)	**IC3**	7 (10.1 %)	Motorcycle + 2 cars: 1 Lorry + bus or car: 2 Car + wall: 2 Car + car or bus: 2	In 5 cases, casualties occurred
	IC4	13 (18.8 %)	HGV + HGV: 1 HGV + car (bus): 3 HGV(s) + cars: 5 HGV + wall: 1 Not known: 3	In all fires, casualties occurred
	Not known	1 (1.5 %)	Not known	Not known

a) Incidents where only smoke is produced without flame are included into single fires.

3.1.1 Incident analysis

No clear trends can be obtained from the analysis that has been applied to all the cases studied. However, based on the comparison between the four categories of tunnel fires, some characteristics can be outlined.

Nearly all collision fires where HGVs were involved (IC4) spread to the next vehicles and resulted in casualties. This implies that these fires are extremely hazardous to road users and special measures should be taken to avoid them. It also indicates that it is likely that the fire brigade will be faced with a sudden increase of gas temperatures and come across a substantial number of evacuating, injured or dead tunnel occupants. In a previous study it was concluded that fires in tunnels involving only one HGV lead to no fatalities, but as soon two or more HGVs are involved, the fire most often leads to fatalities [7].

The collision fires involving only passenger cars at the initial stage of the fires (IC3) did not spread to the neighbouring vehicles. It is reported that the fires were put out easily by a driver or the fire brigade [4]. Although fire spread in single fires is not common (IC2), single fires can propagate to other vehicles when the initial fire originated from a HGV with a large fire load. More attentions should be paid to this type of fire.

3.2 Case study

In this section, three catastrophic tunnel fires are reviewed: the Mont Blanc and Tauern tunnel fires in 1999 and the St. Gotthard tunnel fire in 2001. The reason for selecting these three tunnel fires is that these catastrophic fires showed a number of problems or mistakes related to the fire brigade operations or the technical safety systems. Many useful lessons can be learnt from these three catastrophic fires.

3.2.1 Mont Blanc tunnel fire (1999)

3.2.1.1 A short description of the tunnel

Mont Blanc tunnel is a bi-directional tunnel and started its operation in 1965. The tunnel connects France and Italy and the total length is 11 600 m. Each half of the tunnel is controlled by one operating entity, i.e. ATMB (Autorout et Tunnel du Mont Blanc) in France and SITMB (Societa Italiana del Traforo di Monte Bianco) in Italy. The maximum height of vault-shaped ceiling is 6 m and the width is 8.5 m with a cross-section of approximately 50 m^2 [8, 9].

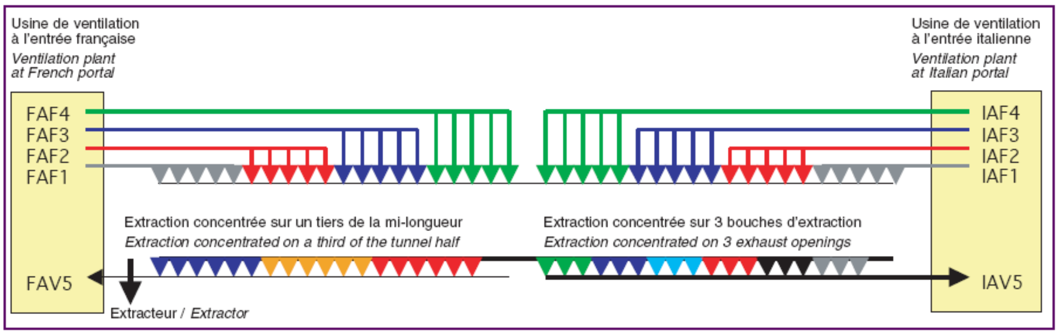
Vehicle rest areas are located at every 300 m and every other rest area has a safe refuge area which is designed to provide fresh air and have a two-hour fire rating. Opposite of the rest areas is a U-turn area. Safety niches are placed every 100 m. They have a fire pull box and two fire extinguishers. In addition there are fire niches every 150 m with water for firefighting [9]. In Table 3.3 the fire protection systems in the Mont Blanc tunnels in 1999 (at the time of the fire) and in 2002 (after refurbishment) are described.

There are four supply air ducts which start from each portal. Each supply duct, accounting for a quarter of the half length of the tunnel, can provide 75 m^3/s of fresh air. A maximum supply flow of 300 m^3/s is possible at each portal, and consequently a total of supply air of 600 m^3/s is possible for the entire tunnel. Originally, a fifth duct was installed to remove polluted air and smoke from fires with an exhaust capacity of 150 m^3/s, through exhaust openings in the vault.

Table 3.3 The fire protection systems before and after the 1999 fire [10].

At time of fire (1999)	After refurbishment (2002)
Safety niches at every 100 m containing a fire pullbox and two fire extinguishers.	Fire-resistant stainless steel cladding fitted to walls.
Fire niches at every 150 m with water supply for firefighting.	Concrete-lined pressurized emergency shelters at every 300 m (37 in total), fitted with fire doors and connected to a safety corridor parallel to the tunnel.
Alarm and fire detection system.	
Pressurised safe refuge or emergency shelter at every 600 m with two-hour fire rating (18 in total) without a safety.	A total of 116 smoke extractors at every 100 m.
Outdated ventilation system with ducts underneath the roadway and limited smoke extraction capacity.	Heat sensors at both ends of the tunnel to detect overheated trucks before they enter the tunnel.
Two command and control centres at both ends with a firefighter team at the French entrance.	Three command and control centres; the newly added central centre has a round the clock firefighting team.
Traffic signals every 1.2 km.	More traffic lights and flashing warning signs.

The exhaust duct was changed to be able to work as a supplemental air supply duct as well as the exhaust one. This enables a total of 450 (300 + 150) m^3/s fresh air to be supplied to the tunnel bore or 900 m^3/s to the entire tunnel. Further, in the French half, the exhaust duct was modified to enable concentration of the exhaust capacity in any of the one-, two- or three-thirds of the half length. On the Italian side, individual motorized dampers were built at each exhaust opening to focus the exhaust on any of two to four openings. Both modifications result in a reduction of the exhaust flow. For example, 65-85 m^3/s for exhaust over a single third of the tunnel half on the French side and 70-90 m^3/s for exhaust by four opening on the Italian side instead of 150 m^3/s for the whole half-tunnel as planned in the original tunnel design [11]. The principal configuration of the ventilation system is shown in Figure 3.1.



FAF: Supply air duct on the French side.
IAF: Supply air duct on the Italian side.
FAV: Reversibel duct on the French side.
IAV: Reversibel duct on the Italian side.

Figure 3.1 Mont Blanc tunnel ventilation system configuration [12].

After the fire in 1999, some fire protection systems were upgraded as shown in Table 3.3.

3.2.1.2 Overview of the incident

On March 24 1999, an HGV carrying 9 tons of margarine and 12 tons of flour started to produce smoke when driving through the tunnel and stopped about 6.5 km from the French portal [13]. Shortly after stopping, flames could be seen and the fire spread to the trailer. The fire continued to spread to other vehicles at a high rate. A total of 26 vehicles (including a motorcycle) on the French side and 8 HGVs on the Italian side were trapped in the smoke and later ignited. Thirty nine drivers and passengers died including a fireman who was evacuated out of an emergency shelter. Most of the victims were found dead in or near their cars [9]. The origin of the initial fire was believed to occur in the engine compartment of a HGV's cab. The fire could be extinguished 53 hours after its ignition [12]. Note that Ingason [8] estimate the fire duration in the Mont Blanc fire to be in the range of 9 – 13 hours. Ingason based his estimation of the total estimated heat content and the maximum heat release rate. The fire duration time was defined by Ingason as the time when the HRR (Heat Release Rate) is 3 % of the maximum HRR. Chronology of Mont Blanc tunnel fire in 1999 is shown in Table 3.4. The decision to enter the tunnel was governed by other considerations that purely when the fire was actually burning.

Table 3.4 Chronology of Mont Blanc tunnel fire (1999) [9, 11, 13].

Time	Time after alarm (min)	Chronology of the incident
10:46	-6	A truck stopped at French toll plaza.
10:52	0	An opacimeter in rest area 18 detected smoke from the HGV and raised alarm.
10:53	+1	The HGV stopped at the location 6500 m away from French portal. A French tunnel operator realized that a fire had happened.
10:54	+2	An Italian tunnel operator received a call from lay-by 22 (about 300 m away from the incident)
10:55	+3	The French and Italian regulators closed the toll. An ATMB agent enters the tunnel and is stopped shortly after rest area 18 (about 750 m from the originally-caught-fire truck)
10:57	+5	ATMB light fire engine entered the tunnel with 4 men form French portal. There was an alarm from lay-by 21 (use of a fire alarm push button)
10:57 ~ 11:01	+5 ~ +9	The employees of Italian toll companies entered the tunnel.
10:58	+6	There was an alarm showing the lifting of a fire extinguisher from rest area 21. The French tunnel control centre alerted the public rescue services.
10:59	+7	ATMB rescue vehicle with 2 men entered the tunnel from French portal.
11:02	+10	The first rescue vehicle of Chamonix left its base. The Italian tunnel control centre alerted the Courmayeur (Italian) fire brigade.
11:04	+12	The first Italian firefighting vehicle of Courmayeur left its station.
11:05	+13	A French patrolman came within some 10 m of the HGV on fire from Italian portal.
11:08	+16	ATMB light fire engine could not advance further after 5400 m due to smoke. They went into the shelter located at lay-by 17 (5100 m away from the French portal).

Time	Time after alarm (min)	Chronology of the incident
11:09	+17	ATMB rescue vehicle was blocked by the smoke after 5100 m. They went into the shelter located at lay-by 17.
11:10	+18	The first high power fire engine of Chamonix (French) reached the tunnel portal.
11:11	+19	The first Italian fire engine entered the tunnel.
11:16	+24	The Italian firemen were stopped by smoke at lay-by 22 (about 300 away from the incident). They had to retreat to lay-by 24 (900 m away from the vehicle) with another 2 Italian firemen and wait rescuers for about 3 hours.
11:15 -18	+23-26	The French fire engine was stopped by dense smoke at 3700 m of the French portal. The firefighter had to escape to lay-by 12 (3600 m away from the French portal) and wait for rescuers for 5 hours
11:32 -36	+40-44	A second French fire engine entered the tunnel to rescue trapped French firemen. However, rescuers failed to reach lay-by 12 and was forced to stay at lay-by 5 (1500 m from the French portal).
12:55	+2h 3	A rescue operation started from the French side.
13:04	+2h 12	The Specialized Rescue Plan for the tunnel was activated on the French side.
About 14:16	+3h 24	5 Italian firefighters were evacuated through the ventilation duct.
15:00	+4h 8	The five Italian firefighters were evacuated.
18:35	+7h 43	All the trapped fire and rescue teams from the French side were rescued.
+53 h		The fire was extinguished.

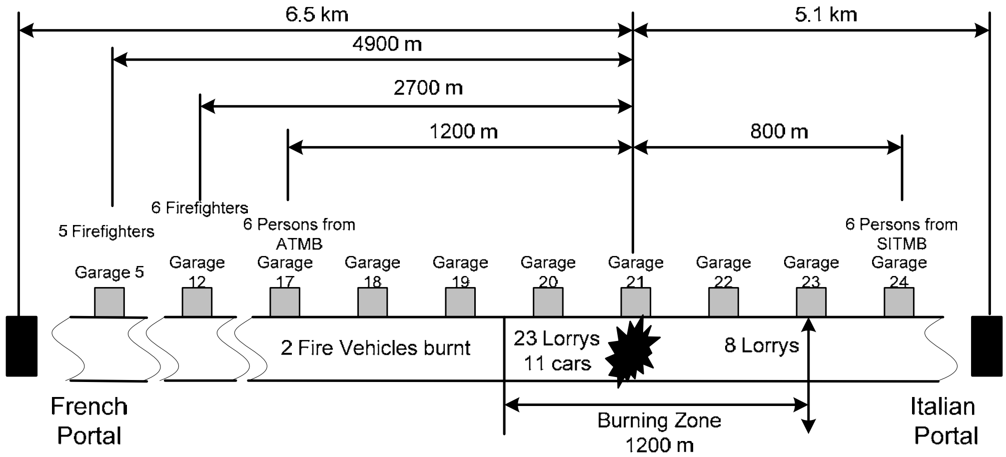


Figure 3.2 Location of involved vehicles and trapped people [13].

3.2.1.3 Analysis on fire operations

3.2.1.3.1 Fire alarm and arrival at the tunnel

An opacimeter – a device used to determine the level of transmission of light through the meter – detected smoke from an HGV and raised the alarm about one minute prior to the

HGV stopping at the location 6500 m away from the French portal. An ATMB light fire engine on the French side entered the tunnel with four men in five minutes after detection of smoke of the opacimeter (in this section, all time indicates the approximate duration time after detection of smoke of the opacimeter). An ATMB rescue vehicle with two men rushed to the fire scene seven minutes after the alarm. On the Italian side, some patrolmen headed for the fire site between 5 and 9 minutes after the detection. After about 13 minutes, a French patrolman from the Italian portal managed to come as close as approximately 10 m from the HGV caught in the fire. Both ATMB fire vehicles and rescue vehicles could not progress further. Sixteen minutes after the alarm, ATMB fire vehicles were forced to stop at 5400 m and ATMB rescue vehicles also stop at 5100 m from French portal by the heavy smoke.

The French public fire brigades were informed by the tunnel control centre six minutes after detection of the alarm. A fire engine from Chamonix on the French side arrived at the tunnel entrance after 18 minutes. However, it was blocked by the smoke at 3700 m from the French portal and had to escape to lay-by 12 (3600 m away from the French portal) 26 minutes after the alarm. A second French fire engine entered the tunnel to save trapped French firemen. However, they failed to reach lay-by 12 and were forced to stay at lay-by 5 (1500 m from the French portal).

On the opposite side, the Italian tunnel control centre alerted Italian public fire brigade (Courmayeur) after 10 minutes. They entered the tunnel after 19 minutes but could not go further due to dense smoke at lay-by 22 (about 300 m away from the incident). Later they retreated to lay-by 24 (about 900 m away from the incident) and waited rescue after 24 minutes.

3.2.1.3.2 Situation evaluation and selection of strategy

According to the translation from the French technical investigation report [9], it seems that the first French fire brigade arriving from the vicinity of the portal tried to approach the incident scene without basic information concerning the situation at the incident. This hypothesis is based on the fact that no information can be found in the report [5] that the French control centre kept in touch with the fire brigade on its side and provided the team with situation information which might help the incident commander to grasp the overall picture of incident and to set up an appropriate strategy. In addition, it appears that the first response team did not try to contact the control centre. Accordingly, the first response team from the French side could not grasp the general situation, which resulted in failing to clarify the strategic and tactical priorities of their operations, i.e., whether the top priority was to attack the fire or search and rescue trapped people. Without establishing strategies and tactics, they could not even ask the control centre what it should do to help fire brigades to reach the scene easily and start their operations effectively. Tactical coordination between the French and the Italian sides could not be expected under these circumstances. Finally, failure of grasping the overall picture of the situation caused the first arriving French team to be trapped in a shelter and to wait for their colleagues for rescue. It also forced top incident commanders on the French side to focus their operations on saving trapped firefighters, rather than searching for civilians trapped in the tunnel or fighting the fire.

3.2.1.3.3 Ventilation strategy

Ventilation systems are one of the vital facilities to save lives and assist fire fighting operations inside tunnels. For that reason, the ventilation strategy should be designed systematically at the planning stage and be able to be changed according to the firefighting strategy employed during operation.

In the Mont Blanc tunnel fire (1999), improper regimes for ventilation systems have been criticized as the main cause of development to a catastrophic fire incident [11]. The airflow that carried the smoke mostly towards France was essentially due to the unbalanced ventilation levels between the two halves of the tunnel, i.e. higher supply of fresh air and absence of exhaust on Italian side. Lacroix [11] pointed out that this imbalance increased fire intensity and certainly contributed to destratification of the smoke. If the operator had reversed airflow in the duct and concentrated extraction around the fire, the airflow would not have brought more smoke towards the Italian portal and the air velocity would have been lower towards France. The ventilation systems did not work as it was supposed to operate and the operations of the ventilation systems were not harmonized with the fire brigade’s operations. Ventilation regimes before and after alarm are shown in Table 3.5. Also, the smoke progress during the fire is shown in Figure 3.3.

Table 3.5 Ventilation regimes before and after alarm [11].

	French side			**Italian side**	
Duct no.	Portal gallery	1-4	5	1-4	5
Before 10:55	Exhaust 2/4	Supply 2/4	Exhaust 2/4	Supply 2/3	Supply 1/3
After 10:55	Exhaust 4/4	Supply 4/4	Exhaust 3/4	Supply 3/3	Supply 3/3

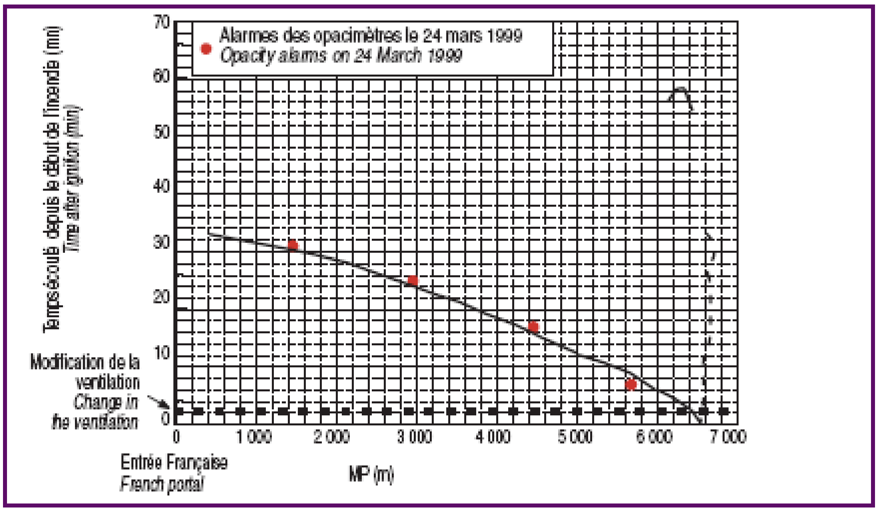


Figure 3.3 Smoke progress during the Mont Blanc fire [12].

3.2.1.3.4 Search and rescue

It is not found in the public investigation report [9] whether search and rescue operations for tunnel users were made by the public fire brigade on each side of the tunnel. However, it is confirmed that evacuation of some drivers on the Italian side was made with help of the patrolmen. The translation of public investigation report [9] revealed that the fire brigades in the two countries did not know how many people were trapped inside the tunnel until 22:30 the day after the incident.

There was a possibility that some people were still alive for some time while waiting for rescue which is indicated by a fact that a pull box alarm was set off in rest area 22 on the Italian side. Also, an alarm followed by removal of a fire extinguisher was registered on the French side in refuge area 21 approximately five minutes after the first detection.

However, it seemed that search and rescue was impossible because the first responders on both sides were trapped by smoke and sheltered waiting for rescue. Therefore, all efforts were made to rescue trapped firefighters rather than civilian tunnel occupants.

3.2.1.3.5 Firefighting

It appears that there was only one chance to attack the fire before it developed to a catastrophic fire. The public report wrote that a French patrol man who was at the Italian portal at the time of the alarm, managed to come within some 10 meters of the fire. At this short distance it would have been possible to fight the fire, if firefighting equipment such as fire engines, nozzles and trained people with protective cloth had been in the vicinity. Unfortunately, appropriate fire resources were not prepared at that place and time. The French patrol man was equipped with only a hand held extinguisher and no protective cloth. Soon, he had to retreat away from the fire because of increasing heat and spread of toxic gases from the fire. The nearest fire brigades, the ATMB on the French side, were blocked by the smoke and the heat, far from the scene. The opportunity to tackle the fire was not given again until the fire became small after destroying many vehicles around the initial HGV fire.

3.2.1.3.6 Comparison with previous fires

Seventeen truck fires have been recorded in the Mont Blanc tunnel since 1965 [9]. For comparison a minor fire is compared here to the 1999 fire.

This minor fire occurred on the 11th of January in 1990. A truck which was travelling from Italy to France produced smoke and stopped at 5.81 km from the entrance. The driver raised the alarm and made a passenger car coming from France turn back. Safety personnel coming from France and Italy were blocked by the smoke at about 8 minutes after the alarm, only about 150 m away from the truck. Fortunately, two French firefighting patrols succeeded to coming within 3 m of the truck with their tanker engine within 10 minutes after the alarm and successfully fought the fire. Thirteen minutes after the alarm, the fire in the truck cab was extinguished; the entire back of the truck was on fire, but the truck was nevertheless accessible. Sixteen minutes after the alarm, the fire on the trailer was controlled by the Courmayeur firefighters. The cargo consisted of 20 tons of industrial cotton spools, wrapped in plastic bags. A total of 10 to 12 tons were burned in the fire [9].

The similarity between the fires in 1990 and in 1999 concerns the fire location, and the progress of the situation at early stage as well as the response time of fire brigades. The largest difference between the two is whether French patrol men could start to extinguish the fire or not at the time they were able to get close to the fire (up to 3 m in 1990 and 10 m in 1999), and whether they had access to fire fighting equipment (yes in 1990 but no in 1999), but there were also other dissimilarities. For example the type of cargo, the direction of the vehicle and ventilation conditions (it is assumed, as this cannot be confirmed from the report [5]). Depending on the success or failure of extinguishing the fire at around 10 minutes, the consequences were totally different; the one in 1990 is regarded as a minor fire with no loss of lives and no fire spread while the fire in 1999 developed into a catastrophic fire where 39 people died and 34 vehicles were destroyed. A more detailed comparison of two fires are presented in Table 3.6

Table 3.6 Comparison of two fires in Mont Blanc tunnel.

Comparison items	**Minor fire in 1990**	**Major fire in 1999**
Classification	**Minor fire**	**Catastrophic fire**
Fire location	5,55 km (from French portal)	6.5 km (from French portal)
Fire cause	Not available.	Engine compartment
Vehicle on initial fire	An HGV	An HGV
Cargo	20 tons of industrial cotton spools, wrapped in plastic bags.	9 tons of margarine and 12 tons of flour
Accessible distance and time	About 3 m after 10 minutes from the alarm.	About 10 m after 13 minutes from the alarm of detection.
Extinguishment	Truck cab: 13 minutes after the alarm. Trailer: 16 minutes after the alarm.	53 hours after ignition.
Consequence	Casualty and damage are not known but most likely minor.	34 vehicles are damaged. 39 people died. Closed for three years.

3.2.1.4 Discussion and lessons learned

After review and analyses of the incident and the operations of fire brigade, a few suggestions for improving working procedures can be derived.

- It is important for tunnel operators to collect situation information necessary for establishing appropriate operational strategies as soon as possible. Situation information includes: type of incident (i.e. collision and subsequent fire or single fire), the number and types of vehicles involved and the number and location of trapped people. Situation information can be gathered by emergency telephones, from eye-witnesses, alarms from detectors or pull boxes, or video monitoring systems such as cameras and CCTV.

- Collected information should be transmitted to the incident commanders of the first arriving teams as soon as possible. Fire brigades should choose appropriate strategies and supporting tactics, based on the collected information, ongoing situation on their arrivals, their previous experience and available resources until they start their entrance into the tunnel.

- The operations on each side of the tunnel should be cooperated and coordinated to maximize the efficiency of their work and to minimise danger to firefighting personnel on both sides. Close communication between both ends of the tunnel should be maintained during operations.

- Proper control of ventilation systems should be made in accordance with selected strategies and tactics on operational stages. Ventilation systems are one of the essential components of safe concepts for tunnels. This can enable evacuees to escape to refuges by providing fresh air or facilitating the removal of toxic gases and smoke. In addition, this can improve the environment for firefighting and rescue. On the other hand, incorrect operation of the ventilation systems may make it difficult for tunnel users to escape or hamper the access or operations of fire brigades. In the Mont Blanc tunnel case (1999), inappropriate ventilation regimes was regarded as one of the causes for the increased intensity of the fire and spread of heavy smoke.

- Adequate firefighting equipment and protective gears are necessary for fighting violent tunnel fires and withstanding the high heat and toxic gases which may be expected to be generated in such fires. Not all ATMB members of the French side were equipped with breathing apparatus when they were called to the fire. This resulted in their being trapped in a shelter and the death of a leader of ATMB.

- It may be the best option for fire safety of tunnels if independent fire brigades are prepared on the both sides of tunnels. The Mont Blanc tunnel had its fire response team only on the French side, not the Italian side. When the French fire team could not approach the fire scene due to the smoke and heat in 1999, the chance to tackle the fire was abandoned because there was no fire brigade on opposite side. After some time passed, when the Courmayeur fire brigade, Italian public fire brigade and others further from the tunnel, arrived at the tunnel, it was too late to approach the fire.

- Tunnel fires should be attacked before they develop and spread to neighbouring vehicles. It is true that this claim can be applied to all kinds of fires. However, it is more significant in the case of tunnel fires than open-air fires because of the characteristics of the tunnel itself, e.g., limited access and enclosed environment which cause difficulties in firefighting and evacuation.

3.2.2 Tauern tunnel fire (1999)

3.2.2.1 A short description of the tunnel

The Tauern tunnel, a bi-directional traffic tunnel, is located in the province Salzburg in Austria linking the region Pongau and Lungau. It is an important tunnel on the north – south connection between Germany and Italy and Slovenia. Ranking among the longest frequently travelled road tunnels in Austria, this tunnel was completed in 1975 with a total length of 6 400 m. The tunnel is 9.5 m wide and 5 m high. The north entrance of the Tauern tunnels is at Flachauwinkel (Salzburg), while the southern entrance is at Zederhaus (Lungau) [14]. The daily traffic is just under 15 000 vehicles, 19 % of which are HGVs [15].

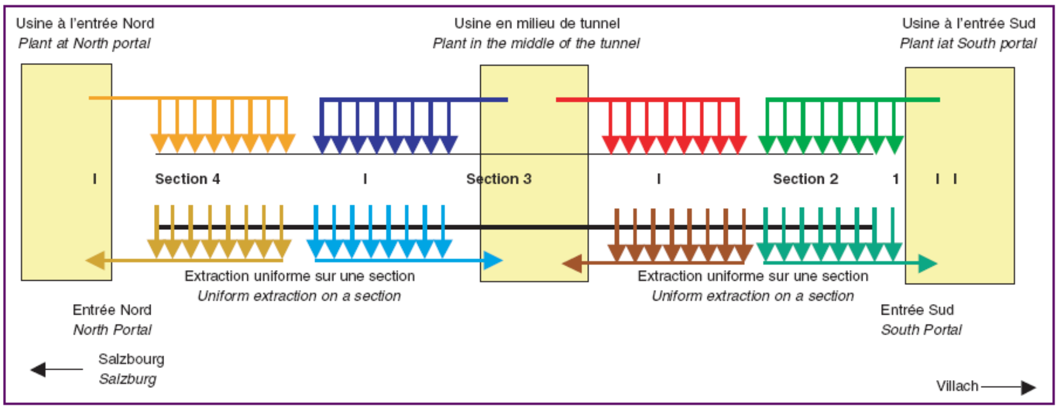


Figure 3.4 Principal configuration of the Tauern tunnel ventilation system [12].

The ventilation system is a fully transverse ventilation system with 4 independent ventilation sections. Sections 1, 2 and 3 are 1500 m long while section 4 is 400 m longer than the others, i.e. 1900 m. The Sections 1 and 4 are ventilated by ventilation plants located at portals whereas Sections 2 and 3 are supplied through a 590 m high shaft situated in the middle of the tunnel [12]. By ventilation calculation, it is known that the maximum volumes of fresh air supply and air exhaust are approximately 190 m^3/s/km and 115 m^3/s/km respectively. Smoke and exhaust air are to be blown out through the exhaust air openings located at every 6 m in the tunnel ceiling [8]. The ventilation system in Tauern tunnel is shown in Figure 3.4.

There are no separate evacuation routes. Emergency call niches, at every 212 m, have fire alarm push buttons, telephones, and two fire extinguishers. Fire niches, every 106 m, provide water supply for firefighters and contain 120 m long hoses, foam nozzles and reserves of emulsifier. Cameras are located every 212 m and monitored in the control centre. By means of traffic radio channel, alarm messages can be sent into the tunnel during an emergency [12].

3.2.2.2 Overview of the incident

On the 29th of May 1999, a truck loaded with various types of spray cans, including paint of class 9 dangerous goods, was travelling north. It had to stop behind a number of vehicles already waiting in front of the traffic lights due to the repair work of the tunnel. Behind the truck, four private cars pulled up and were waiting. Another HGV following the cars tried to stop after finding that the cars in front of it had stopped. However, it could not avoid a collision 750 m from the north portal. The collision resulted in destroying the four cars and subsequent leakage of the fuel tank of a car. The fuel ignited and started spreading to other vehicles. The details of the operations of the fire safety facilities and fire brigades will be discussed in Section 3.2.2.3. The fire was under control after about 12 hours after start of the fire. Ingason [8] estimated the fire duration to be 7 – 10 hour. The estimated duration time is based on estimated fuel load and maximum HRR and derived as the time when the HRR is 3 % of the maximum HRR. The damage of the fire was catastrophic; 12 people died, 16 HGVs and 24 cars were burned, tunnel walls over a length of 350 m and the carriageway surfacing and the niches over a length of 900 m were damaged [8]. The fire location and chronology are shown in Figure 3.5 and Table 3.7, respectively.

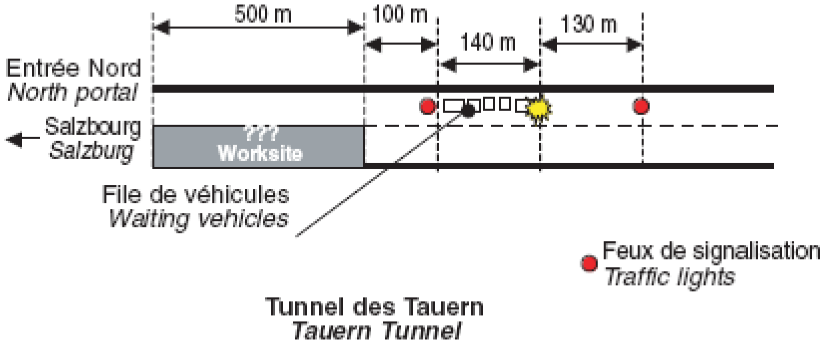


Figure 3.5 Fire locations in Tauern tunnel in 1999 [12].

Table 3.7 Chronology of Tauern tunnel fire (1999) [8, 12, 13, 16].

Time (Minutes)		Chronology of the incident
4:48	0	A lorry loaded with paint stopped. Four cars behind the lorry also stopped. Another lorry could not stop at the red light and crashed into four cars. Fuel spilled and ignited soon. 8 people inside the crashed cars died as a consequence of the incident.
4:50	+2	**An automatic fire detection system set off an alarm.** Although the alarm automatically switched the traffic lights at the entrances of the tunnel to red, still more cars entered into the tunnel from the south. The manager in duty alerted the fire brigades located at both ends of the tunnel. <u>When the fire started, the fire alarm started the ventilation system in 230 m^3/s into the exhaust-air duct installed in the ceiling but no fresh air was supplied through the other three sections of the ventilation system (only through portals).</u>
4:53	+5	The first extinguisher was removed from the housing. 4 lorry drivers tried to take cover inside an emergency phone box about 100 m from their vehicles but only 2 men and a woman managed to do so as the smoke obstructed everything.
4:54	+6	Three lorry drivers alerted the control room. They all could survive with the help of rescuers.
4:57	+9	The volunteers of Flachau at the north were alerted. They had 18 km uphill to reach the portal with their 16-ton-engine. **At the south, the voluntary fire brigades Zedernhaus and St. Michael received the alarm.** They were 7 km away from the tube. Until now they only know that heavy smoke came out of the tunnel portals.
5:15	+*27*	**The voluntary Fire Brigades Zedernhaus and St. Michael entered the tunnel from South with a light fire vehicle and heavy pump water tender.** **As the air-stream had been directed to the north, the firefighters wearing BAs (Breathing Apparatus) proceeded towards the fire scene.** They got informed about the three people captured in a phone cell further on. The commander of the firefighters gave the order to switch to maximum extraction in the part where the fire was while <u>the third ventilation section was then turn to full supply (5:30).</u> **The firemen managed to reach the phone cell where three people were trapped. (6:00).** The three drivers received survival filter masks and were immediately brought outside. **In order to move forward they extinguished 7 lorries and 12 cars over a distance of 400 m.**
9:15	+4h 27	**It was decided to withdraw the firefighters from south and attack the fire from north. For this purpose, the direction of the airflow was changed.** <u>The third section of the ventilation system was switched to extraction, thereby pushing the smoke towards the south and into the exhaust-air duct.</u>

Time (Minutes)		Chronology of the incident
		Up until this point there had been no chance to attack the fire on the north side because of the amounts of smoke and the intense heat.
10:00	+5h 12 min	Large parts of concrete began to fall from the ceiling.
11:00	+6h 12 min	The direction of wind was changed to give the possibility of additional ventilation from the north. It is reported that the temperatures slowly began to drop.
11:00-15:00	+6h 12 - +10h 12 min	No attempt to fight the fire from the north portal was made due to the risk of collapse.
15:00	+10h 12 min	The firemen started extinguishing from the north with a heavy pump water tender equipped with a remote water cannon using firefighting foam.
17:00	+12h 12 min	The fire was proclaimed under control.
21:00	+16h 12 min	**The fire was extinguished.**

Note: In the table, normal front: [15], **bold** : [13], underline: [8].

3.2.2.3 Analysis on the operations of fire brigade

3.2.2.3.1 Situation evaluation

With insufficient information gathered, it is difficult to find out how well the first response units were informed on the situation inside the tunnels while they were rushing to the incident scene or when they arrived at the tunnel. However, it seems that the only information they had were that a large-scale fire had occurred and was in progress in the tunnel, because they could see the smoke coming out of the tunnel portals. It is thought that they had to approach the fire to obtain more information so they could set up appropriate strategies and supporting tactics for the fire.

Fortunately, information concerning trapped people was transferred early to firefighters wearing BAs (Breathing Apparatus). After that the strategy was to save people in danger and supporting tactics were employed systematically; ventilation systems extracted smoke from trapped people and rescue crews wearing protective cloths and BAs were able to approach to them. The rescue operations ended in saving three people and after that the strategy was changed to control the fire and subsequent actions were taken.

It appears that all operations relating to evaluation of situation and selection of strategy were properly and timely performed, based on information available at that time.

3.2.2.3.2 Access routes

The first approach was made from the south, probably because fire brigades on the south side were located closer to the tunnel than those on the north side. The firefighters on the south managed to get close to the fire scene under very dangerous circumstances. However, they were blocked by the smoke. Fortunately, as trapped drivers were on their side, firemen on the south could save the three drivers from the tunnel with the help of the ventilation system.

Considering the rapid development of fire and insufficient firefighting resources, it is clear that it was almost impossible to access to the fire close enough to control the fire through the north portal. It was a wise decision not to enter the north portal and wait or prepare their operations.

3.2.2.3.3 The control of ventilation systems

When the fire started, a fire alarm triggered the ventilation systems which created a longitudinal air flow to the south. However, when three drivers were found to be trapped in the smoke, the ventilation system was modified to ensure the access to the phone box where the trapped people stayed. After rescue and fire extinguishing work on the south part had been done, the direction of the airflow was changed again. The ventilation systems had good extraction capacity so it could prevent the smoke spreading to the north when access and attack from the north was initiated.

In conclusion, ventilation operations and the control of air flow were satisfactorily performed. The smoke progress during the fire is presented in Figure 3.6.

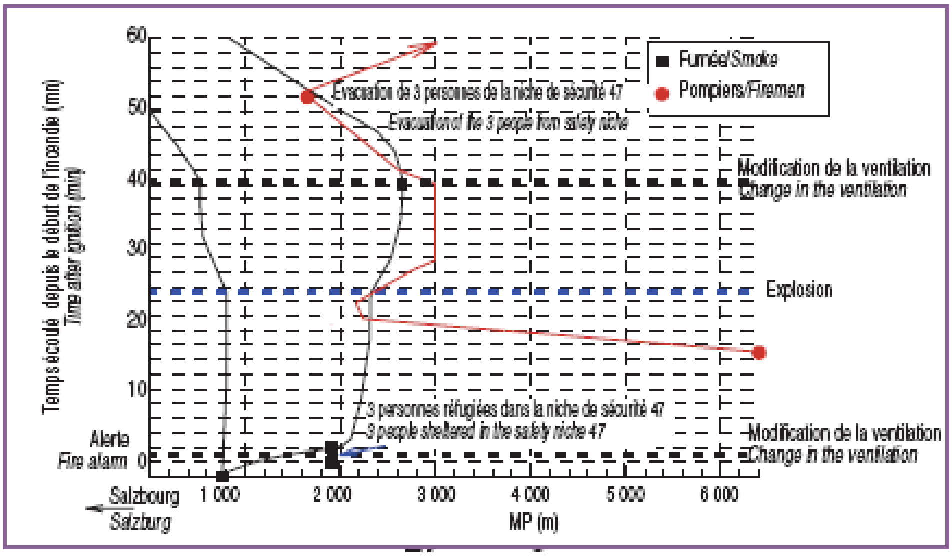


Figure 3.6 Smoke progress during the Tauern tunnel fire [12].

3.2.2.3.4 The cooperation between the fire brigades on each side.

There is no indication of close cooperation between the fire brigades on both ends and fire brigades and the control centre can be found in Table 3.7. However, some facts in Table 3.7 indicate that efficient coordination and communication between the two portals was maintained throughout fire services' operations. Ventilation systems were controlled and modified in connection with the selected strategies and supporting tactics. Approach to and withdrawals from the fire scene were harmonized and controlled, i.e. approach from one side and withdrawals from the other side.

3.2.2.3.5 Rescuing or evacuation

Twelve people were killed in this incident. Eight died as a direct consequence of the initial collision and four as a consequence of the fire. Three victims were found in their vehicles. Evidently they did not or were unable to flee. One lorry driver escaped towards the south and died from smoke intoxication [13] and 86 people managed to flee, 47 of which were injured [14].

Although many people were injured, rescue operations were successful. Three trapped people were saved under extremely difficult conditions such as toxic smoke and long travel distance by foot. The first response team from the south was equipped with proper breathing apparatus (BAs) and ventilation systems forced the smoke away from the trapped drivers and rescue crews. It was almost impossible to rescue the four people who died due to smoke inhalation.

3.2.2.3.6 Firefighting.

The catastrophic fire consumed 16 HGVs and 24 cars even though the fires on 7 HGVs and 12 cars were extinguished rather early on the south part [13, 14]. Since the fire spread and increased very rapidly, the fire authorities might not have had any alternative than to wait until the fire became small by itself after having consumed the material involved in the fire. In addition, the initial strategy was set to rescue three people trapped in the tunnel and all firefighting resources were put to rescue operations. There were no resources left to control the fire.

3.2.2.4 Discussion and lessons learned

In this section, previous fires occurring in Tauern tunnel are compared to each other. The aim of the comparison is to find out which factors cause an initial fire to develop to a large fire. It is hoped that comparison of various types of fires that have occurred in the same tunnel can show a sharp contrast of the causes which affect the outcome of the fires. The reason is that fires occurring in the same tunnel have the same geographical conditions, geometry of tunnel and distance from the fire stations.

Four fire incidents have been reported in the Tauern tunnel until 2007 [4]. A short descriptions of these incidents are presented in Table 3.8. Among the four incidents, three cases are regarded as minor ones; these fires could be brought under control quickly by firefighters or the drivers. In addition, there were no reported injuries in them. Unlike the three minor fires, the fire in 1999 can be defined as a major fire because it caused many casualties and significant economic loss and it is reported that the fire brigade had many difficulties in dealing with the fire.

The comparison given in Table 3.8 shows a distinctive difference between the minor fires and the major one. The number and types of vehicles involved in the initial fire seems to be the determining factor that influences the outcome. More specifically, the fire that occurred in 1999 was found to be difficult for an average fire brigade to handle, which was caused by multiple collision involving at least two HGVs. On the other hand, the three minor fires involved only one HGV (one lorry) or two passenger cars. These lorries had lower fire loads than that of one HGV in the incident in 1999. Notice that this comparison is based on very limited information. See also the study by Lönnermark discussiong the outcome of fires involving different numbers of HGVs [7].

Table 3.8 Summary of previous Tauern tunnel fires. See Appendix for more details on these fires.

Date	Classification	Vehicle at origin of the fire	Cause	Consequences	Extinguishment
2002, 18 Jan.	Minor fire	A lorry	A faulty engine	No casualty	Fire brigades were able to bring the fire under control very quickly
2001, 10 July	Minor fire	Two cars	A head on collision	Casualty is not reported.	The fire was extinguished quickly by the driver of one of the cars
2000, 10 Jan.	Minor fire	An HGV	Not available	Casualty is not reported.	The fire was dealt with rapidly and was extinguished within half an hour by firefighters on both sides of the vehicle.
1999, 29 May	Major fire	Multiple collision involving HGV's and cars.	Front-back collision and fuel leakage.	12 dead. 16 HGVs and 24 cars were destroyed.	The fire could be extinguished in about 15 hours from the ignition.

3.2.3 St. Gotthard road tunnel fire (1999)

3.2.3.1 A short description of the tunnel

St. Gotthard tunnel is situated in Switzerland, between Airolo (1 145 m above sea level) and Göschenen (1 081 m above sea level). The tunnel is part of the Swiss A2, one of the major European road connections through the Alps, which connects the Italian border (Chiasso) with Germany and France (Basel) [17]. The tunnel, opened in 1980, is 16 918 m long, 7.8 m high and 7.8 m wide with 41 m^2 cross-section. The type of ventilation is transverse with six ventilation sections, six ventilation stations, 4 ventilation shafts and 22 fans. Fresh air is evenly provided by means of ports installed in the lower part of the sidewalls at the interval of about 16 m. The exhaust extraction is done through fixed exhaust nozzles located in the false ceiling at the distance of 8-16 m. The ventilation systems have 2150 m^3/s (additionally 30 % reserve) of maximum fresh air flow rate and 2150 m^3/s of max exhaust flow rate. The peak fresh-air and exhaust rate are 125-130 m^3/s/km. Under normal operating conditions, the tunnel is ventilated either in a transverse or in a semi-transverse mode. In transverse mode, the fresh air and exhaust fluxes are even in each ventilation sector. In semi-transverse mode, the fresh-air injection fans are operated normally while the exhaust fans are inactive and the exhaust is extracted by open by-pass dampers located at base of the ventilation shafts [17]. St. Gotthard tunnel ventilation system configuration and air flow in the tunnel immediately before the fire are presented in Figure 3.7 and Figure 3.8 respectively. Detailed information on the tunnel and the incident is shown in the work edited by Borghi and Perugini [18].

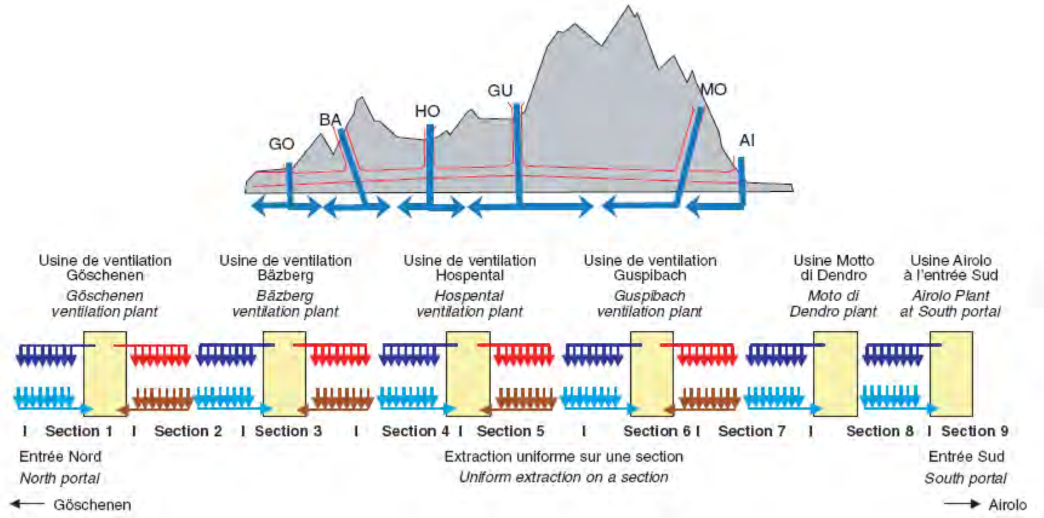
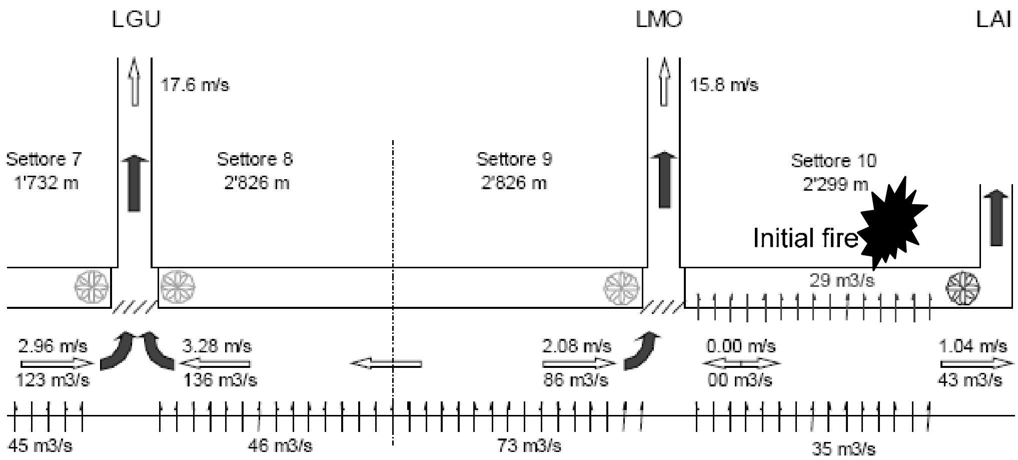


Figure 3.7 Principal configuration of the St. Gotthard tunnel ventilation system [12].



Note: LGU indicates Guspibach ventilation plant.
LMO indicates Moto di Dendro ventilation plant.
LAI indicates Airolo ventilation plant.

Figure 3.8 Air flow in the tunnel immediately before the fire [19].

The tunnel has a parallel safety tunnel with 8 m^2 cross section and 64 shelters every 250 m. The shelters connecting the traffic section with the safety tunnel are pressurized and protected on both sides by fire-resistant doors [17]. SOS niches with phones and fire extinguishers are spaced at every 125 m and connections to the hydraulic systems are installed every 250 m. The piping for the hydraulic systems is located in the safety tunnel but connections are inside and outside the shelters [17].
An around-the-clock firefighting team is situated at each end of the tunnel for quickest response. One firefighter was added to each 3-man-team after a severe truck fire incident in 1997 [9].

3.2.3.2 Overview of the incident

An HGV carrying various goods, among them photographic film rolls, was driving from the south to north portal on 24 October of 2001. It collided against the right wall of the tunnel and then rushed into the opposite lane and hit the left wall at 1.1 km from the southern entrance. On the opposite lane, another HGV loaded with tyres was on its way to the south. The two HGVs collided on their right sides between lanes. It is reported that the diesel spilled from the first HGV evaporated and ignited by a short circuit generated by a battery. The fire seemed to spread very rapidly [17].

As a result of the fire, 11 persons lost their lives and 8 others were sent to a hospital. A total of 23 vehicles (13 HGVs and 10 cars) were damaged. The fire location and involved vehicles are shown in Figure 3.9. To distinguish between vehicles involved in the incident, vehicle number and its description are allocated in Table 3.9 and Figure 3.10. The direct damages were reported to be 16 million CHF [17]. The tunnel had to be shut down for 2 months [17]. The chronology of St. Gotthard tunnel fire (2001) is presented in Table 3.10.

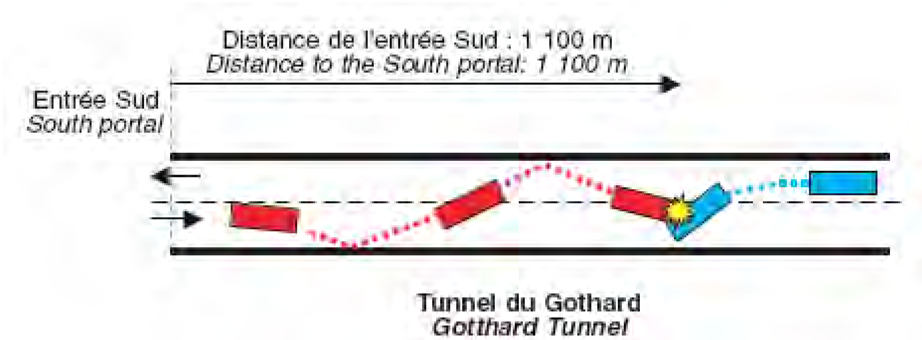


Figure 3.9 Fire location in the St. Gotthard tunnel in 2001 [12].

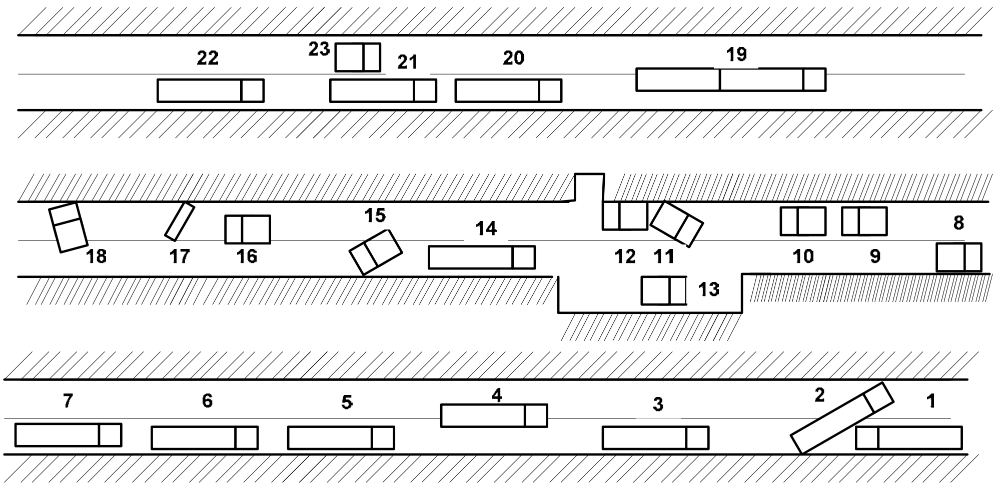


Figure 3.10 The vehicles involved in the St. Gotthard tunnel fire (2001) [17].

Table 3.9 Vehicle number allocation and description [20].

Number	Description
1	The Belgian HGV (carrying a mixed cargo, mainly clothes and textiles), initially travelling north, which was partially burned out after the fire.
2	The Italian HGV (carrying a cargo of vehicle tyres), initially travelling south, which was totally burned out after the fire.
3 – 7	Five HGVs, initially travelling south, some partially, some completely, burned out.
8-13	Six light vehicles which were behind the HGVs. These were not burned but did suffer damage through exposure to heat.
14	A truck, covered in soot, not damaged by heat.
15-18	Light vehicles, covered in soot, not damaged by heat.
19-22	Four HGVs, covered in soot, not damaged by heat.
23	A light vehicle, covered in soot, not damaged by heat.

Table 3.10 Chronology of St. Gotthard tunnel fire (2001) [20].

Time (Minute)		Chronology of the incident
09:39	0	Collision between 2 HGVs. Both lanes were blocked.
09:40	+1	Emission of smoke at the incident location. Discharge of a liquid on the roadway.
09:41	+2	Ignition of the fire at ground level, underneath the HGVs. Automatic fire alarms were triggered. The fire brigades in Airolo were alerted automatically. The fire brigades at Göschenen were informed of the incident.
09:42	+3	Fire spread onto the trailer of HGV 2. All the emergency and maintenance services in Airolo were alerted.
09:43	+4	The passenger from HGV 4 left the tunnel via the safety gallery. The driver returned to the cabin of HGV 4 where he died.
09:46	+7	The firefighters (approaching from the south) were not able to get within 15-20 m of the vehicles due to the ferocity of the blaze.
09:47	+8	The firefighters from Airolo began their operations. The first people evacuated the tunnel to the south, using the safety gallery. North of the incident several people also evacuated the tunnel and found refuge in the safety gallery.
09:49	+10	Some small explosions, attributed to the bursting of tyres, were heard. At the location of the incident, the door between the safety gallery and the tunnel could not be opened because of very high temperatures.
09:51	+12	Road police began evacuation of vehicles on the southern side of the incident. HGVs were reversed to the portal.
09:52	+13	The Göschenen fire brigade arrives at a location approximately 2.5km north of the incident.
09:59	+20	The driver of HGV 21 made a phone call. He lost consciousness and died in the cabin.
10:17	+38	The ceiling collapsed above HGV 1.
10:28	+49	The ceiling partially collapsed on HGV 3.
10:58	+79	The heat in the vicinity of HGVs 1 and 2 meant that it was impossible to enter the tunnel from the safety gallery at this location.
11:02	+83	The fire involving HGV 1 was extinguished.
11:03	+84	The ceiling collapsed above HGVs 4 to 6.
12:55	+196	Start of fire-fighting procedures at HGV 7.
14:00	+261	(time very approximate) The fires involving HGVs 3 to 7 were extinguished.

3.2.3.3 Analysis on the operations of the fire brigade

3.2.3.3.1 Evaluation of the situation and selection of strategy

It is not clear how well first response teams were informed before they came to the fire scene. However, Airolo firefighters on the south side realized quickly how extensive the fire was and what had happened before they arrived. They saw furious flames coming towards them as the two vehicles colliding with each other started to burn. The firefighter started to extinguish the fire on the first HGV. Due to their efforts, in combination with the ventilation conditions, there was no fire spread towards southbound vehicles. Further, the back part of the trailer of Belgian HGV initially travelling north did not start to burn.

It took some time for Göschenen firefighters (on north side) to learn exactly what was going on. It was difficult for them to judge the situation until they were able to get closer to the fire scene through the safety gallery. Any type of search or rescue efforts from the north side would have been impossible at that time. The only possible strategy was to fight the fire immediately after they entered the tunnel from the safety gallery. The fires on HGV 2, 3 and 7 (See Table 3.9) developed rapidly and reached its peak in the early phase of the fire.

3.2.3.3.2 Response and Access toward the incident scene

Arrival of fire brigades at the scene was rapid and without delay. The firefighters in Airolo from the south side could get close to the fire scene. They were able to reach up to about 20 m after 7 minutes from the collision and five minutes after the fire alarm. The rapid arrival was possible as an Italian truck driver whose truck was hit by HGV 1 instructed the traffic entering the tunnel from the south to turn back. It is thought that the fire could be fought only from the south side at early stage of fire development. This in turn was found to be insufficient.

On the north side, Göschenen fire brigade arrived approximately 2.5 km north of the incident after 13 minutes from the collision. However, at first, they were not able to advance further due to the smoke logging created by the longitudinal air flow headed from the south to the north. The longitudinal velocity of this flow was relatively high. Finally, the firefighters managed to access to HGV 3, 4 and 7 through the refuge or escape routes. They started their operations after some time delayed. However, it should be noted that due to high thermal exposure it was impossible for the firefighters to enter the tunnel from the nearest safety gallery in the vicinity of HGVs 1 and 2.

It was reported that several vehicles had been abandoned on the north side of the incident due to unsuccessful attempts to turn their vehicles [17]. The abandoned vehicles may have made the access of north fire brigade difficult. Their decision to use the safety gallery as an access route was correct and resulted in good results.

3.2.3.3.3 The control of the Ventilation

It is reported that the ventilation systems worked properly. However, they were not able to extract all the smoke from the tunnel. The resulting nominal smoke-extraction rate was of the order of 86 m^3/s/km [17] and it can be estimated that the smoke could have propagated over a length over 2 km. The propagating smoke generated further alarms, which activated the smoke extraction from the powerful ventilation stations in Motto di Dentro and Guspisbach (See Figure 3.7 and Figure 3.8). This sustained the existing longitudinal velocity and smoke propagation from south to north [17]. The plot with propagation of the smoke is shown in Figure 3.11. There is no reporting on the modification of the regime of the ventilation systems or any attempt to reverse the direction of air flow. The initial fire mode appears to be maintained throughout the fire period.

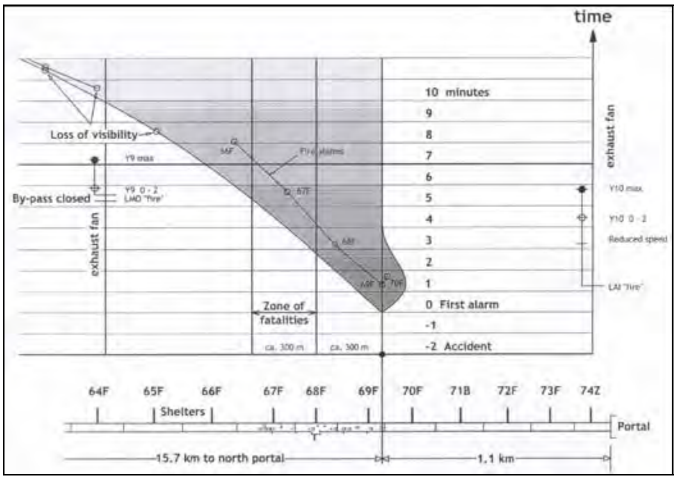


Figure 3.11 Plot showing the propagation of smoke [19].

3.2.3.3.4 The cooperation between the fire brigades

It appears that the two groups of fire brigades on the both sides worked independently. There is no evidence or comments found in relevant documentation which show any type of coordination or harmonization of fire strategic operations between fire brigades. For example, an attack on one side was carried out at the same time as a withdrawal was carried out on the other side.

3.2.3.3.5 Evacuation and rescue

It was reported that 23 vehicles, including 13 HGVs, were trapped on the north side. The number of people in the tunnel when the fire started is not clear. The number of people that could escape into the shelters is not known, but was certainly in the order of 30-35. [17]. The road police started the evacuation of the road users on the southern side of the incident. On the north side of the incident; several people evacuated the tunnel and found the way to the safety gallery [20]. All 11 victims were found on the northern side of the incident. With one single exception (an HGV driver, who decided to return to his vehicle after escaping), all victims were found over 300 m from the fire origin. The shelters and their doors resisted the heat and smoke and contributed to the rescue of many road users [17].

The fire brigade had limited possibilities to begin evacuation or rescue operations. All 11 victims were believed to be dead within about 20 minutes after the fire started. This is supported by the fact that the driver of HGV number 21 made a phone call but lost consciousness and died in the cabin approximately 20 minutes after the collision. Last victim were found in the vicinity of HGV 21. At that time, Göschenen fire brigades on their sides were far away from them. At about 13 minutes after the fire, Göschenen fire brigades arrived at a location approximately 2.5 km north of the incident. As the smoke travelled so fast from south to north, some people could not help being affected even though they were at a distance from the fire that could be regarded as safe. It appears that self-evacuation was the only alternative.

3.2.3.3.6 Firefighting

Firefighting operations by fire brigades on both sides were well performed. They succeeded in limiting the fire to HGV 1 and 2 on the south and preventing fire spread to the north behind HGV 7. Vehicles behind HGV 7 did not catch fire but were only damaged by heat and soot.

3.2.3.4 Discussion and lessons learned

St. Gotthard tunnel fire in 2001 gives some valuable information to help fire authorities to develop or revise their operational procedures for road tunnel fires.

Firstly, it is almost impossible for an average sized fire brigade to deal with this kind of fire incident, i.e. an abrupt collision between HGVs with heavy fire loads. It also shows that it is extremely difficult to tackle propagating fires in tunnels. In the St. Gotthard tunnel in 2001, even though firefighters were faced with abruptly and quickly developing fire, they rushed to the scene and started their operations without delay or mistakes. However, they could not prevent the fire from propagating and save people trapped in the tunnel.

Secondly, it is not easy to access the fire scene through the safety galleries when the fire is fully developed. The firefighters participating on the north side gave testimony that it was impossible to enter the tunnel from the safety gallery at the location of HGVs 1 and 2 due to the heat [20]. More research needs to be carried out in order to find out effective ways to access the scene downstream of the fire through the safety galleries.

Thirdly, the modification of the regime of ventilation systems should be considered on the basis of the progress of the fire and subsequent variation in tactics while fire brigades fight the fire. In the St. Gotthard tunnel fire, it was pre-programmed that the initial regime of ventilation should be maintained throughout the duration of the fire. It is not clear, with the limited information available, whether a change of direction of air flow was necessary or not. However, if the air flow had been reversed from north to south when the fire involving HGV 1 was extinguished, the operation on the north would have been made more easily and safely and it would have resulted in less damage to the vehicles and the tunnel structure.

3.2.4 Comparison between three major fires

In this section, the focus will be on the response of the fire brigades first at the fire scene in order to develop some advice for more effective firefighting and rescue operational procedures for road tunnel fires. This will also help to understand the characteristics of fire operations in road tunnels and evaluate the work done by fire brigades and emergency teams and operations of the safety facilities. The comparison between the three major fire incidents is shown in Table 3.11.

Table 3.11 A comparison between three major tunnel fires

Items	Mont Blanc tunnel fire (1999)	Tauern tunnel fire (1999)	St. Gotthard tunnel fire (2001)
Type of scenario (cause of fire)	Single fire and fire spread (IC2). (Technical defect)	Collision fire and fire spread (IC4). (Front-rear collision)	Collision fire and fire spread (IC4). (Head-on collision)
Estimated causes of rapid progress of the fire.	Fuel leakage in engine compartment. Supply of the fresh air. High fire loads (margarine and flour)	Fuel leakage onto road surface. Multi collision. High fire loads (various types of spray cans)	Diesel spill on road surface. Explosion of tyres. High fire loads (film rolls and tyres)
Original fire location	An HGV with much combustible goods.	Between multi collided cars and HGVs	Between HGVs collided each other.
Number of involved vehicles	26 vehicles and 8 HGVs	16 HGVs and 24 cars	13 HGVs and 10 cars.
Estimated time for control of fire	About 53 hours	About 16.1 hours	About 6.2 hours

Items		Mont Blanc tunnel fire (1999)	Tauern tunnel fire (1999)	St. Gotthard tunnel fire (2001)
Accessible distance to a fire and duration time to the distance.	From the south	**Italian side**: about 10 m after 13 min (patrolman) (since the first alarm was raised)	500 m after about 30 min (since the collision happened, the author's estimation)	15 - 20 m after 7 min (since the collision happened)
	From the north	**French side**: about 2800 m after 23 min.	There was no attempt to access from the north.	2500 m after 13 min.
Work of the earliest response team.	From the south	The patrolman could not advance and went back into the shelter.	They were blocked by the smoke. Later, they advanced further and rescued the trapped.	The firefighters started their operations and succeeded in protecting the rear part of the HGV and stopping the fire spread.
	From the north	French teams had difficulty in advance and had to escape to the shelters.	They did not enter the tunnel for a long time.	They were seriously hampered in their approach.
Ventilation		Transverse type with 4 supply air ducts and 1 reversible duct.	Transverse ventilation with 4 ventilation sections.	Transverse ventilation with 6 ventilation stations and 10 ventilation sections.
Initial air flow direction		From Italian side to French side (south to north).	From north to south direction.	From south to north.
Emergency fresh air		Maximum fresh air to ventilation section containing fire	Cut fresh air to ventilation section containing fire.	Cut fresh air to 30% of full capacity ventilation section containing fire.
Variation of the air flow.		No	Yes	No
Coordination and cooperation between fire teams		No	It appears to be made.	It appears not to be made.
Successful work		1. Rescue work for the firemen through the reversible duct.	1. Variation of the ventilation mode. 2. Success of the rescue of the trapped people.	1. Rapid response. 2. Access to the scene by the safety gallery. 3. Prevent the possible fire spread to upstream.
Non successful work		1. Asymmetrical location of the fire teams. 2. Inadequate ventilation operations. 3. The shortage of the protective equipment and training. 4. No cooperation between both ends. 5. The malfunction of the fire detectors. 6. Delayed response time.	None.	1. No attempt to change of the direction of the air flow. 2. Automatic systems for the operation of the ventilation increased the smoke progress.

3.2.4.1 Lessons learned from the three major fire incidents.

Lessons learned from the comparison above are presented in Table 3.12.

Table 3.12 Lessons learned from the three major fires.

Items	Lesson
Access route	It is clear that access to the fire scene on the downstream side of the fire was nearly impossible, particularly in the case of large fires. In all the three major fires discussed here, the fire brigades could not reach the fire even if they approached the fire soon and with the longitudinal flow in their back. More rapid arrival of a fire brigade might improve the chance to approach the fire sufficiently to be able to attack the fires. Further, safety galleries can help firemen to approach the fire. But experience shows that entering to the tunnel through the cross passages of the safety galleries could be dangerous because of the heat and smoke inside the tunnel.
Arriving time.	It is difficult to determine an acceptable arriving time that is applicable to all the tunnel fire scenarios. However, it is clear that fires caused by collisions do not allow much time to access them. In the St. Gotthard tunnel fire, it is assumed that after 7 minutes after the collision, firefighting would no longer be possible. In case of fires caused by technical defect of the vehicles, firefighters have generally more time before conditions become critical.
The control of the ventilation	The firefighters should have good knowledge of the air flow inside the tunnel and emergency operations of ventilation systems of the tunnels prior to an incident. Also, various tactics should be made according to the combinations of the ventilation mode and the natural air flow .
Variation of the ventilation mode	The variation of the ventilation regimes is one of important parts to be considered during the fire operations. Timely and well-controlled modifications of the mode can contribute to help firemen to approach closer to the fire, protect escaping or trapped people from the smoke and block the spread of fires.
Cooperation and coordination	It is important that coordination and cooperation is made between fire brigades on each end of a tunnel so that one team's operations are not interrupted by another. This is more important in tunnels than in normal buildings because of limited access routes to the tunnels and the difficulty in controlling the smoke.
The location of the emergency teams	The emergency response teams should be prepared at both portals of the tunnels, within the similar response time, if possible. Catastrophic consequences may result if the responsibility of response is given to only one side. The case of Mont Blanc fire shows this clearly.

Items	Lesson
Duration of the fire	The duration times of these three fires are in all cases more than 6 hours. This means that when the first response failed and the tunnels were not equipped with fixed water spray systems, it was not possible to extinguish fires until they became small through fuel depletion. If the tunnel is a part of a critical transportation infrastructure, the tunnel should be protected by fixed water spray systems.
The necessity of fixed water spray systems.	Related to the problems on resources available, controversial issues need to be raised. When trapped people are reported and the primary strategy is set to rescue them, there is a risk that the fire will develop into a catastrophic event. Fixed water spray systems can be a solution for this problem. The fire occurring Tauern tunnel in 1999 was dealt with without manifest operational mistakes and delay of fire brigade. However, the fire brigade could not prevent the fire developing into a catastrophic one. This fact supports the necessity for installation of automatic water spray systems such as sprinkler or water mist systems in road tunnels where there is a risk for catastrophic fires.

4 Previous findings of important parameters

When a fire brigade establishes its operational procedures for road tunnels, it may be useful to look for the results or findings obtained from related research and experiments carried out in the past. In this section, several key factors are reviewed which can play an important role in the development of strategies and supporting tactics. On the basis of these factors, some recommended operational procedures are proposed in Chapter 6.

4.1 Temperature and radiation

The gas temperature and flame radiation are the key factors to be considered for firefighters. These two parameters can affect access to the tunnel. The possibility to obtain access to the fire from downstream or upstream, within an accessible distance and operation time is determined by the ability of firefighters to withstand the radiation.

Temperatures and radiation were measured in the Runehamar tunnel tests in 2003 [21]. In four tests, gas temperatures were measured at different distances from the seat of the fire. The temperature above the centre of the fire reached over 1000 °C within 10 minutes after ignition. The maximum heat release rates in these tests were 202, 157, 119 and 66 MW, respectively [22]. These test fires developed quickly. On the downstream side of the fire, all gas temperatures were above 200 °C up to 200 m from the fire within 10 minutes after the ignition. In about 15 minutes, the temperatures reached their maximum at a given distance. These high temperatures indicate that with this fast developing and high peak HRR (202 MW), it is impossible for firefighters to reach the fire from downstream. The temperatures did not drop below 100 °C for about 50 minutes after the ignition. In France, the target criterion for gas temperatures for fire brigade personnel is set to about 100 °C [23]. If any fire brigade enters the tunnel from the downstream with a fire like T1, they will be exposed to a high heat radiation. They may end up in danger and in worst case they can be trapped in the tunnel and have to wait for their colleagues' help, which was the case in Mont Blanc tunnel fire in 1999. In Table 4.1 the maximum temperature during Test T1 at different distances from the seat of fire is presented.

Table 4.1 Maximum gas temperature in test T1 at selected distances upstream and downstream of the fire (°C) [21].

Position	70 m from the fire	100 m from the fire
Upstream	153	95
Downstream	785	570

It is nearly impossible for the fire brigade to access the fire scene for firefighting from upstream under conditions like those in fire test T1. These tests demonstrate how severe and dangerous the working conditions for fire brigades are.

Radiation is an important factor for firefighters. The Runehamar tunnel tests in 2003 presented various useful information about upstream radiation exposure. Figure 4.1 shows radiation values measured 10 m upstream of T1, T2 and T3. Peak radiation values upstream of the HGV fires in four tests are listed in Table 4.2 [24].

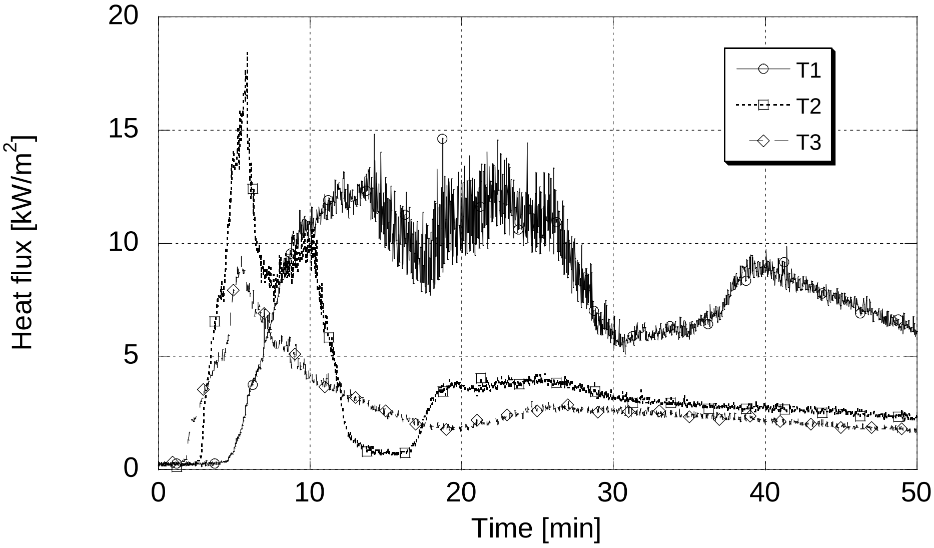


Figure 4.1 Radiation 10 m from the upstream end of the HGV set-up in the Runehamar tests (T1 to T3) [24].

Table 4.2 Peak radiation values upstream of the HGV fires in the Runehamar tunnel. The distances are measured from the upstream end of the HGV set-up [24].

Test id	**Radiation 5 m upstream of the fire [kW/m^2]**	**Radiation 10 m upstream of the fire [kW/m^2]**	**Radiation 20 m upstream of the fire [kW/m^2]**
T1	80	14	2
T2	35	18	3
T3	20	9	2
T4	40	10	4 (15 m)

In Figure 4.1, radiation levels in T1, T2 and T3, 10 m upstream of the HGV set-up, exceed 5 kW/m^2 within about 7 minutes after ignition (5 kW/m^2 is the French radiation criteria for fire brigade). These radiation values indicate that fire brigade could arrive at the scene up to 10 m from the fire at that time. At this distance the entire fire can be expected to be covered with water. The firefighters should start to discharge water to the target within a short time in order to control the fire size. At later time the firefighters would only be able to reach to 20 m from the fire and start to attack the fire with water spray which may not be able to extinguish the fire but can decrease the radiation and temperature of the fires, thereby enabling the fire brigade to advance further to the fire. Once the fire brigade is able to advance up to 10 m from the fire location, direct attack to the fire with jet water will be possible. It seems to be possible to reach to 20 m from the fire with 202 MW of peak heat release rate all the time after ignition because Table 4.2 shows that at 20 m (15 m in T4) upstream the fire, peak radiation values do not exceed 5 kW/m^2 in all four tests. However, it should be noted that these assumptions and expectations are based on the fact that other compounding factors, i.e. backlayering, high temperature, fire spread and water supply are not considered.

It is expected that radiation values downstream of the fire will be much higher than those upstream so it will be more difficult for the fire brigade to approach the fire from downstream than from upstream.

4.2 Fire size or peak heat release rate

It is important to know the maximum size of fire that can be controlled by an average-sized fire brigade. Unfortunately, there is limited information in the literature on this issue. To deal with this question, incident reports and testimonies from fire brigades were examined. In total, 20 descriptions of firefighting by fire brigades or tunnel users were found among the 69 fire incidents presented in Appendix 1. The lists of the fire incidents containing firefighting descriptions are presented in Table 3.1. It shows that when no more than two passenger cars or a bus were involved in the fire, the fires were reported to be extinguished with no difficulty by fire brigade or tunnel users, regardless of the types of the incident. Fires in HGVs, caused by mechanical faults that did not spread to the cargo, could be suppressed by the fire brigade before the fire developed into a catastrophic fire. Among 20 fires for which there is information on firefighting, only four fires were not able to be tackled in early stages by the fire brigade: Mont Blanc tunnel fire (1999), Tauern tunnel fire (1999), St. Gotthard tunnel fire (2001) and Frejus tunnel fire (2005). In two cases (Tauern and St. Gotthard) the fire was caused by a collision between vehicles or fuel spills and developed so fast that their cargos caught in fires. The spread made the fires become too large for the first response fire brigade to combat the fires.

Another way to obtain the acceptable response limit for an average fire brigade is to use an equation which shows the relationship between HRR, distance from the fire source and radiation level. HRR can be calculated from the following equation [25]:

$$q_s'' = 1/3 \cdot Q/(4\pi R^2) \qquad (4.1)$$

Where q_s'' is the radiation level, Q is the total heat release rate and R is the distance from the effective point source to the place where the firefighters are located.

Tests show that firefighters with protective clothing feel pain after approximately five minutes when they are exposed to a radiation of 5 kW/m^2 [24]. In addition, the experiment presented in section 5 shows that about 10 m from the end of the simulated trailer is the optimum distance for fighting the fire when considering the coverage of water. When it is supposed that durable radiation level for firefighters with protective clothes is 5 kW/m^2 and the optima attack distance is 10 m, the HRR is approximately 20 MW calculated by equation 4.1. This gives information about what levels of HRR we can expect.

Based on witness reports from fire brigades, incident history and equation (4.1), the following conclusions can be drawn concerning the response limit of an average fire brigade:

- The upper limit for the response of an average fire brigade is a fire involving up to two passenger cars, a bus and a car burning at the same time or one HGV where the fire start in the vehicle and does not spread to the goods on the trailer at an early stage of the fire. This is of course also dependent on the type and amount of goods found in the trailer.

A rough estimate of the response limit of an average fire brigade is 20–30 MW. This is, however, based on a limited amount of information and is dependent on many factors such as type of vehicle, cargo, ventilation, tunnel height, access to water and fire fighting personnel.

Table 4.3 Summary of HRR data from fires in different types of vehicles [24].

Vehicle	No. of tests	Energy [GJ]	Peak HRR [MW]	Average peak HRR [MW]	Time to peak [min]
Passenger car	15	2 – 8	1.5 – 8.5	4.1	10 – 38
2 cars	7	5 – 10	5.6 – 10	7.6	13 – 55
3 cars	1	NA	8.9	8.9	33
Bus	2	41 a)	29 – 30	29.5	7 – 8
HGV trailers	10	10 -244	13 - 202	- b)	8 – 18

a) Information on energy content was only available for one of the buses; the value 41 GJ corresponds to the bus giving a peak HRR of 29 MW.
b) The test set-ups were too different for an average to be of interest.
Estimation of fire size which the first arriving fire brigade can cope with was carried out based on limited information and simple description of activities of people involved in firefighting work. This limit should be noted when the firefighting criteria proposed in this study are applied. In addition, further research should be made on this topic.

4.3 Fire spread and flame length

Fire spread from the initial fire to neighbouring vehicles is one of the key parameters for the possibility to fight the fire successfully. Involvement of more vehicles and cargos through fire propagation increases the heat release rate and temperature and produces more toxic smoke and gases. This results in a situation that is impossible for the fire services, leading to significant casualties and damage of the tunnels. To prevent fire spread or extinguish the fire is one of the main tasks for the fire brigade, not to mention rescuing the tunnel occupants. Preventing fire spread enables fire brigades to perform their task in safer conditions and prevent a minor incident from progressing to a major incident.

Fire spread is closely related to HRR, gas temperatures, distance between neighbouring vehicles, flame length of the fire, and ventilation conditions. Fire spread and these related parameters were studied in the Runehamar tunnel test in 2003. The findings on this subject are summarized below [26]:

- Fire spread was observed by measuring the temperature 0.3 m below the tunnel ceiling. Fire spread to a large target, simulating a second vehicle, was estimated to occur when the gas temperature was above 515 °C.

- Maximum flame lengths in all three tests were 60–100 m within 20 minutes after ignition when a temperature of 600 °C was used to estimate the position of the flame tip: about 95 m, 84 m and 66 m in T1, T2, T3 respectively. The peak HRRs were 202 MW in T1, 157 MW in T2 and 119 MW in T3.

- Based on the visual observations and results from the measurements, estimated times for fire spread were 6 min for T1, 3.3 – 3.4 for T2 and 4.5 min (observation of video) for T3.

- When the fire spread to the large target occurred, the heat release rate was in the range of 20 MW to 40 MW with about 2–3 m/s longitudinal flow.

The results concerning the estimated and observed fire spread in the Runehamar tunnel tests further imply that tunnel fires can spread in a very short time after the start of fire. At the same time the fire brigade may not be able to take measures combat this and they may be required to move away from the fire to a safe location. Fire brigades should prepare their resources and train themselves with appropriate incident scenarios so that they can block the fire before it propagates.

4.4 Ventilation

The importance and usefulness of ventilation systems for the evacuation of occupants and response of fire brigades are often emphasized in the literature [1, 24]. They point out that ventilation systems can blow all smoke produced by the fire to one side of the fire so that tunnel occupants are able to escape to a safe place. Furthermore, favourable conditions can be provided to the fire brigade for approaching and attacking the fire.

On the other hand, disadvantages of employing ventilation systems are that it can make the conditions inside the tunnel worse by increasing the intensity of a fire, by spreading the fire, or by trapping escaping occupants in the tunnel in smoke and flames. It is well known that ventilation increases the size of a fire. In conclusion, it may seem reasonable that the maximum possible ventilation to control the smoke may worsen the circumstances; but if an optimal ventilation flow can be obtained, ventilation systems can be effective tools to control smoke and heat. Although further research is necessary to better determine the relation between ventilation and fire intensity, ventilation strategies for fire brigades can be recommended:

- Operations of ventilation should vary depending on the type of fire. A minimum ventilation flow, high enough to prevent back layering, should be used for fires involving a HGV or a large fuel spillage and an increased ventilation flow should be used for fires involving a passenger car or a smaller pool fire.

- Adopting a single ventilation mode in the event of any fire in a tunnel does not seem to be the best alternative.

- Possibilities to control the ventilation flow during the later stage of the fire in accordance to the fire brigade needs should be considered.

- If the type of fire is identified by the tunnel operators or fire services, ventilation regimes should be adjusted accordingly.

4.5 Human behaviour in tunnel fires

Knowledge of typical human behaviour in tunnel fires can contribute to the establishment of effective evacuation and rescue plans. This may then be translated into a decrease in the number of casualties and thereby prevent further human losses. Unfortunately, studies of human behaviour in tunnel fires have not been performed in the same detail as those in building fires. The reason is that tunnels are much fewer than ordinary buildings, the conditions in a tunnel fire are more complicated and not so well known [25]. Nevertheless, a few key behaviour patterns are commonly found in some incident reports or in the literature. These behaviour patterns are summarized below:

- Occupants typically sit and wait in the car to obtain more information or in the case of a queue situation the wait for it to start to move. In the fire in the Mont Blanc tunnel in 1999, some victims were found sitting in their cars with their seat-belts on [24].

- The evacuating passengers prefer to move along the tunnel to reach the tunnel entrance instead of using emergency exits [27].

- It is reported that there is a good chance that the passengers may still be alive even after a long period of time. The reason is mostly that the passengers initially could move away from the immediately threat. The fire in the Seljestad road tunnel in Norway showed that four passengers were able to stay in the smoke in the tunnel for over an hour and still survive [4]. Note that the possibility to survival depends on the size of the fire, and the concentration of toxic gases and many other related variables [27].

Based on the knowledge summarized above, it can be expected that fire brigades arriving at an early stage of the fire, will encounter with some problems waiting to be solved; e.g., meeting a number of the passengers trying to evacuate through the tunnel instead of using the emergency exits. They will be delayed as they have to deal with the tunnel users staying in their cars and to find out if there are any other people trapped in the smoke. If this is the case they have to know how the rescue operations should be carried out.

5 Experiment of firefighting distance

5.1 Introduction

Firefighters have to fight tunnel fires before they become too extensive. Before intervention of the fire brigade, some practical considerations should be made. Firstly, a determination of an optimal attack distance between the fire and firefighting nozzle . This distance may depend on the nozzle type and the water flow rate. The optimal attack distance can be defined as the distance from the nearest end of the fire to the nozzle. The water spray from the nozzle should, e.g., cover the entire front side of a trailer which is on a fire. The importance of an optimal attack distance is due to the fact that tunnels may have various obstructions which hinder water reaching the targets. Examples of obstructions are the tunnel ceiling and the trailer cabinet. A firefighter standing too close or too far away is not effective enough to control the fire. It is valuable to find out and know the optimal attack distance where the optimal usage of water is obtained.

5.2 Experimental set-up

An experiment was carried out to find out the optimal attack distances with different types of nozzles and flow rates. To simulate the ceiling of a tunnel, a wood pole was set up beside one side of a steel container. The height of the pole was 5.23 m which can be regarded as typical European clearance heights in tunnels. The spray angle and discharge rate was controlled by a professional firefighter. The firefighter aimed so it would not hit the pole (ceiling). An ordinary steel container was used to simulate the cabinet of a trailer. The container was 12.1 m long, 2.54 m wide and 2.42 m high. Three types of nozzles were employed: Akron, TFT and Fogfighter. While adjusting the angle of discharge under the height of the pole, all efforts was made to make the water hit the entire upper side of the steel container. The discharge pressure of the fire engine was set at 7 bars which is a general setting for fires in ordinary buildings. Observations were made concerning whether the discharged water covered the whole upper side of the container.

After the discharge experiment was finished, another measurement was carried out to determine the difference between the nominal flow rates given on the nozzles and the real volume of water. The experimental set-up and test performance are shown in Figure 5.1.

Figure 5.1 Experimental set-up and tests for the discharge test using firefighting nozzle.

5.3 Experimental results

With the Akron nozzle, three optimal distances were obtained with different flow rates. As expected, the higher the flow rate, the shorter the distance. However, small differences were obtained between the three flow rates. On average, about 11 m can be said to be the optimal attack distance when Akron nozzles were used. As far as TFT and Fogfighter were concerned, it was difficult to obtain the optimal attack distance. With high flow rates, i.e. 320 L/min for TFT and 300 L/min for Fogfighter, 4 m and 10 m were obtained as an optimal attack distance. The results of the experiment are presented in Table 5.1.

Table 5.1 Optimal distances depending on nozzle types and flow rates

Nozzle type	Flow rate (L/min)	Discharge pressure of fire engine (bar)	Optimum extinguishable distance (m)
Akron	115	7	12
	230	7	11
	360	7	9
TFT	320	7	4
Fogfighter	300	7	10

The volume flow of water was measured for comparison with the nominal flow rates for each nozzle. Three measurements were carried out only for TFT nozzles. The results and comparison are shown in Table 5.2 and Figure 5.2.

Table 5.2 Results of the measurement on flow rate

Measurement	The weight of collected water (kg)	Time (s)	Measured flow rate (L/min), A	Nominal flow rate (L/min), B	A/B
1	28	20.8	81	130	0.62
2	41.6	10	250	320	0.78
3	33	6.6	300	500	0.6

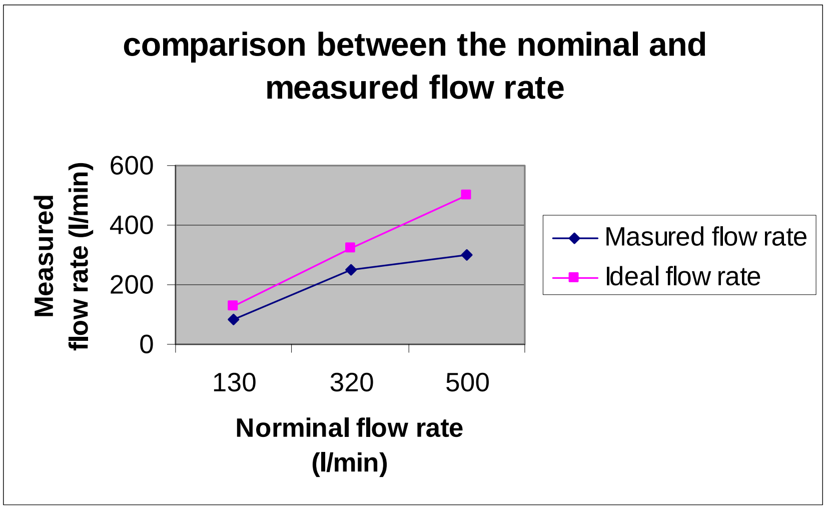


Figure 5.2 Comparison between nominal and measured flow rate

5.4 Application of the results

The results show that with Akron and Fogfighter full water coverage of the target can be obtained within a range of 9–12 m. This means that firefighters should approach up to this distance in order to obtain an effective fire control. In order to advance to this distance, fire brigade should be assisted by the ventilation systems and the water spray which reduces the radiation from the fire.

There is a difference between nominal and measured flow rates. A reduction in the flow rate is caused by inner friction of hoses, joints and the nozzle itself. Firefighters should be aware of these losses in flow rates so that they can select proper nozzles and discharge pressure of water to be able to obtain the necessary water flow rate to fight the fire.

These experiments may have the character of an ad-hoc activity. For example, the determination of “good coverage of water” were made purely by visual observations. This means that the results could be different if the tests were carried out by another person. However, as the purpose of these tests was to obtain an indication and rough estimation of optimal attack distances before the development of the specific operational procedures, the limitations indicated above can be overcome. It should be emphasized that when these results are applied, these limitations should be considered. As far as optimum attack distances are concerned, additional experiments should be in a more controlled manner and with greater participation from the fire brigade.

6 Development of firefighting and rescue operations

6.1 Choice of strategy

Strategies are defined as the general plan or course of action decided upon by the incident commander in order to achieve firefighting objectives which are to protect life and property by performing rescues, and by locating, confining and extinguishing fires. On the other hand, tactics are defined as the operations or actions required to carry out the strategy selected by the incident commander [28]. It is important to select appropriate strategies suitable for the specific situation. The selected strategies and subsequent decisions such as choice of access route and control of ventilation systems are crucial for the outcome of any attack.

There are two types of strategies which can be applied to firefighting and rescue operations: offensive and defensive strategy. An offensive strategy emphasizes the rapid stretching of hose lines to attack the seat of the fire while a defensive strategy may be employed, initially, at large or expanding fire operations where protection of exposures or containment of the fire is critical [28].

Selection and implementation of any strategic plan and its supporting tactics are dependent on an accurate grasp of the fire situation. When the scale of a fire is expected to be beyond the capacity of the first units arriving at the scene of a fire, a defensive strategy should be chosen. In other words, the first responders should put their priority of operations into stopping the fire spread and confining the original fires until their capacity surpasses the intensity of the fire. In contrast, when a fire is initially small or develops slowly so that the first arriving unit can put a fire under control, it is better to choose an offensive strategy for an effective control of a fire.

Related to the capacity of the first units arriving, consideration should be paid to two concepts: response limit and maximum intervention time. The response limit can be defined as the scale of a fire which an average fire unit can cope with. In section 4.2, the response limit is proposed to be a fire in a HGV where the fire does not spread to include all the goods on the trailer. This response limit is estimated to correspond to heat release rates of 20 – 30 MW. As another important concept, maximum intervention time can be defined as the time period from when the average fire brigade can tackle the fire until the fire develops into a catastrophic fire. Maximum intervention time will be discussed in more detail in Chapter 7.

Finally, the key information for determining the outcome of any operation is what types of incident is happening in the tunnel and how fast the first unit on the scene can approach to within the attackable area and start firefighting.

6.1.1 Offensive strategy

Offensive strategies focus on prompt attack of the fire to halt the spread of the fire and remove any threat to escaping tunnel occupants. Thus, under this offensive strategy, <u>firefighting operations are given a priority</u>. Also aggressive approach to a fire should be attempted taking a risk for smoke and heat into account.

Although defensive strategies are selected at the first stage of response operations, change of the strategies into offensive strategies should be considered after the purposes of defensive strategies have been obtained, i.e., to confine the original fire and stop the spread to other vehicles. Also, it is time to change from defensive to offensive strategy when the fires moves into the decay stage so that they can be expected to be under the control by the fire brigade.

6.1.2 Defensive strategy

Defensive strategies can be taken in case of insufficient fire resources and a rapidly developing large scale fire at the time of decision. The purpose of this strategy is to confine the fire into its origin, block fire spread, and search and save endangered tunnel occupants until a favourable environment for offensive strategies can be created. Thus, under the defensive strategy, search and rescue operations are given priority.

Typical examples of operational procedures adopting defensive strategies are:

1. The first access is made from the unaffected tunnel tube or from the upstream side of the tunnel.
2. Search and rescue operation are conducted on the upstream side of the fire.
3. The fire brigades on the downstream side position themselves in a safe location and help the escaping people out of the tunnels or stop the fire spread if it is necessary and possible. They should have a good knowledge on the fire spread and flame length because flame length can be as long as 60-100 m in a short time after the ignition which might put firefighters in danger as well as escaping people.
4. The later arriving teams help the first arriving teams with search and rescue operations or protect the rescuers from the heat and smoke.
5. After the upstream side of the tunnel has been cleared of trapped people and vehicles, the direction of air flow is reversed so that search and rescue can be made on the original downstream side.
6. During the search and rescue on the original downstream side, fire brigades on the opposite sides of the tunnels retreat to safe places and prevent fire spread.
7. Once the fire decreases is enough to be tackled by fire brigades, change of strategy into an offensive one is initiated.
8. When trapped people are confirmed regardless of their locations, saving them is the top priority over any other operation above.

6.2 Obtaining necessary information

Normally, as decision concerning the strategies lies with the incident commander of the first arriving unit, it is very important for the incident commander of the first response team to rapidly obtain as much information as possible concerning the situation on the way to the scene, and to accurately confirm the whole picture of the course of the fire. The essential information which the incident commander should obtain to select proper strategies is:

a. Type of fire: single fire (IC1 or IC2) or collision fire (IC3 or IC4)
   - Single fire: The fist consideration can be given to the offensive strategies unless the alarm and arrival at the scene are too late.
   - Collision fire: It may cause trapped people and oil leakage which make the fire situation complicated. Defensive strategies are preferred first consideration.

b. Number and types of vehicles involved in the original fire.
   - Fire involving only passenger cars: The possibility of fire spread is low. The fires are expected not to exceed response limit. Offensive strategies can be employed.
   - Fire involving at least one HGV or lorry transporting large amount of material: Fire spread can be seen. The size of fires may be greater than the response limit within a

short time after the start of the fire. Defensive strategies should be considered unless special measures have been taken before the incidents.

c. Existence of trapped people.
- When trapped people are confirmed, all resources and operations should be employed to save the lives in danger: to dispatch rescue teams to the people, to blow the smoke and heat away from them and rescue units and to provide guide for survival or air to them.

d. Location of a fire.
- When a fire happens in a twin-bore tunnel, the closest cross-passage from the scene of the fire should be chosen for the rapid approach and response route. The exact location of the fire guarantees the correct selection of the cross-passages.

The information above can be obtained by video monitoring systems and by emergency telephones from witnesses if this equipment is installed in tunnels. Tunnel operators should give the information obtained to the incident commanders as soon as possible and continual communication between the two parties should be maintained until the fire is under control.

6.3 Access routes and approach distance

Access to the fire scene can be made from two directions: upstream and downstream of a fire. Unlike buildings, limited access to a fire is the main problem for road tunnels.

Determination of an appropriate access path has a close relationship to the strategies chosen by the incident commanders when first unit arrives. If an offensive strategy is adopted, access should be made simultaneously from both sides of the fire. In particular, access from the downstream side should be carried out carefully as fire fighters can be heavily affected by the smoke and heat. It is essential for the firefighters to be equipped with appropriate protective gear and obtain reliable information about the fire situation. Further, fire brigades on the downstream side may be faced with large numbers of escaping or trapped people. Appropriate measures should be taken at the planning stage to identify suitable strategies. Examples of access routes under offensive strategies are shown in Figure 6.1.

Figure 6.1 Access routes under offensive strategies.

In order for a defensive strategy to be effective, active firefighting from the downstream should be limited. One exception is when trapped people are expected to be found on the downstream side and this situation requires active rescue operation on the same side. Under such circumstances, the ventilation systems should be used to force the smoke and heat from the firefighters. In other cases, operations on the downstream side fire brigade should be to prevent fire spreads or just wait and prepare for attack when the fire has decayed to a level that is controllable by the fire brigade. On the upstream side, the fire brigade should proceed towards the fire as close as possible and prevent the fire spread, confining the fire until it starts to decay. All these operations should be supported by the ventilation system to obtain a suitable safe environment and to maximise efficiency. Examples of access routes under defensive strategies are presented in Figure 6.2.

Figure 6.2 Access routes under defensive strategies.

In a twin-bore tunnel, the unaffected tunnel bore and the cross passages between the two bores should be used as access route for the fire services. The incident commanders should be informed of the exact location of the fire so that the incident commander can designate a proper cross passage as an access route. The second and third teams arriving should select different cross-passages depending on the strategies implemented on their arrival. Access routes in twin-bore tunnels under offensive strategies and defensive strategies are shown in Figure 6.3 and Figure 6.4.

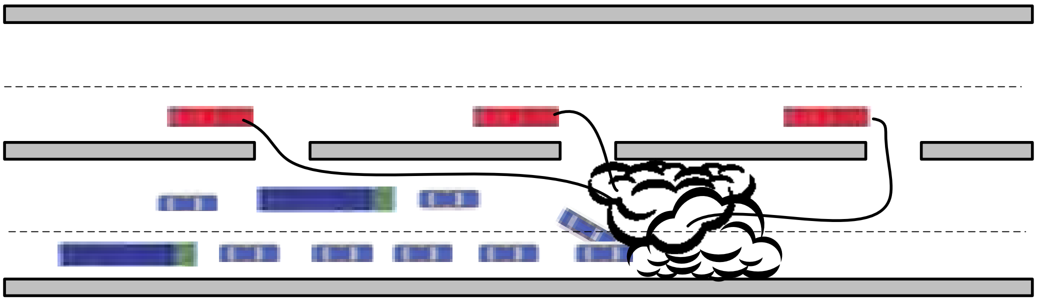


Figure 6.3 Access routes in twin-bore tunnels under offensive strategies.

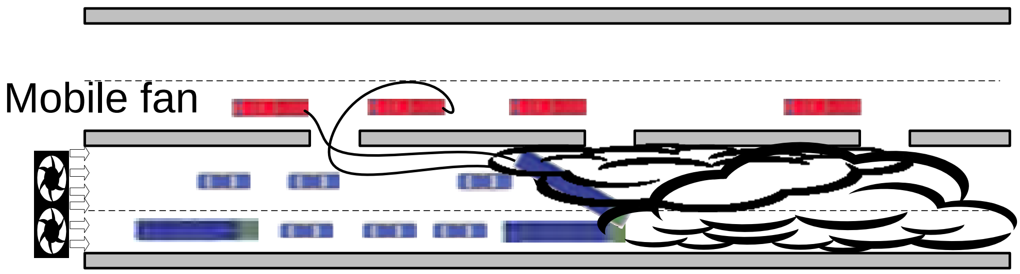


Figure 6.4 Access routes in twin-bore tunnels under defensive strategies.

Fighting a HGV fire in a tunnel with longitudinal ventilation requires approach by the firefighters up to a distance of maximum 10 m. This distance is obtained from experimental data presented in chapter 5. This distance is much less when a fire involving a passenger car in a tunnel is considered. The issue of "optimal attack distance", i.e., the optimal distance from the different types of fires to the hose lines for effective extinguishment, requires more studies.

6.4 Control of air flow

Control of air flow has a significant influence on the consequences of a fire occurring in a road tunnel. The issue of how the ventilation systems should operate depends on the choice of strategy and the determination of the access path. Initial ventilation strategies should be established in advance during fire safety planning steps and work properly as designed in plans when a real fire occurs. During initial ventilation operations, appropriate strategies and access paths are to be determined and subsequent ventilation modes should be modified accordingly. The specific ventilation operations depend on the type of ventilation system:

a. A tunnel with natural ventilation system

- A mobile fan produces the longitudinal air flow through the tunnel which blows out the smoke from the fire brigade approaching to the fire site.
- The velocity of the air flow should be sufficient to preventing the back-layering which is the smoke movement in the upstream direction against the airflow, but no higher. The velocity of the airflow preventing the back-layering is defined as a critical air velocity. Control of air flow under natural ventilation systems is shown in Figure 6.5.

Figure 6.5 Control of air flow under natural ventilation systems.

b. A tunnel with longitudinal ventilation system

- Blow the smoke away from the access route of the fire services. It helps the fire brigade to approach to the site of the fire while being less affected by the smoke.
- Air flow should be maintained at the speed of the critical air velocity. Too high air flow, more than a critical air velocity, may worsen the fire situation.
- The direction of the air flow can be changed by reversing of the ventilation fans.

Control of air flow using a longitudinal ventilation system is shown in Figure 6.6.

Figure 6.6 Control of air flow under longitudinal ventilation systems.

c. A tunnel with transverse ventilation system

- Extraction of the smoke from the affected sections or areas of a fire.
- No supply of fresh air through unaffected sections or areas.
- Above operations generate and maintain a longitudinal air flow which enables fire brigades to access to the fire scene.
- Reverse or control of longitudinal air flow can be obtained by using the air supply from one of the neighbouring sections or areas while maintaining the extraction of the smoke from the affected sections or area of the fire.

Control of air flow using a transverse ventilation system is shown in Figure 6.7.

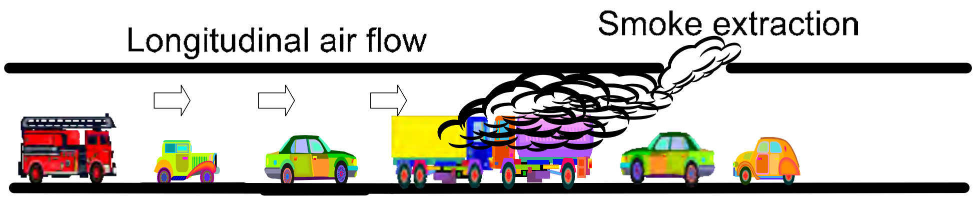


Figure 6.7 Control of air flow under transverse ventilation systems.

6.5 Rescue operations

It is clear that top priority should be the rescue operations rather than any other work of fire brigade. If someone is confirmed to be trapped, all efforts and resources should be concentrated on saving them.

Information about trapped people can be obtained by emergency telephones and surveillance cameras inside the tunnels. The places where trapped people stay and wait for help can be specially designed structures for them, such as emergency shelters or other alternative enclosures. It is reported that trapped people can survive even outside of shelters for a longer time than generally expected if they are not in direct contact with the smoke. A typical example is the Tauern tunnel fire in 1999. Three people in a phone cell survived for more than one hour after the fire started and were brought outside. Even though the phone cells are not designed for shelters, they managed to use the phone cell as a shelter.

This case implies that the possibility of trapped people should always be kept in mind and search for them both on upstream and downstream sides should be carried out even if a fire has already been at its peak. During search and rescue work, firefighting operations should be controlled or coordinated in order to support rescue operations and not to endanger trapped people and rescue teams. For this purpose, control of air flow and harmonization between firefighting and rescue teams is essential.

6.6 Cooperation between fire brigades at different portals and jurisdictions

The tragic fire of the Mont Blanc tunnel in 1999 shows how poor cooperation between two fire brigades placed at different ends of a long tunnel can severely exacerbate a bad situation. The operation of the ventilation system, which did not follow the planned procedure, resulted in a situation where the French fire team was exposed to danger. In addition, the lack of communication between the French and Italian fire brigades in the initial stage of the response hindered them from effective use of their insufficient resources.

In spite of the importance of cooperation, it is not easy to establish a proper cooperative relationship between two portals. In general, it is often found that long tunnels lie under different jurisdictions. Furthermore, many tunnels are under the control of fire brigades and operation companies of different countries. The more fire brigades or operation companies are involved, the more problems in the communication can occur. This is especially true when a tunnel passes through the border of two countries. In this case the language barrier may lead to misunderstandings or the disregard of cooperation between the opposite parties. The issue of the cooperation can be discussed separately in the following three categories:

a) A tunnel under one jurisdiction
  - All operations should be coordinated and controlled by the highest ranking officer at the site of the incident. Also, all operations should be performed in accordance with firefighting and rescue plans.
  - The responsibility for control is passed up the chain of command.
  - The incident commander on each end should report to and follow the decision of the highest commander who controls the overall situation.

b) A tunnel under more than one jurisdiction.

- A unified public firefighting and rescue plan must be developed before the opening of the tunnel. This plan should clarify the principle of unified command and control.
- The safety plans and common operation procedures should be checked and updated through regular meeting and joint drills involving fire brigades and tunnel operators.
- For multi-national tunnels, the most important issue is to overcome the language barrier. Measures against misunderstanding due to language differences should be taken during the development of safety plans.

6.7 Operations under fixed fire suppression systems

The suggestions concerning firefighting tactics and operations given previously should be reconsidered if a water spray or water mist system is installed. This has not been dealt with in the report, but one should be aware that the tactics may need to be significantly revised in such cases. The tactics may be different depending on whether an automatic or manually operated system is installed. In general, one could say that a water spray or water mist system should benefit the firefighting conditions.

Until now, it is reported that fixed fire suppression systems have been installed in Australia, Austria, Japan, Korea, Holland, France, Spain, Norway, Sweden and USA. In Japan and Korea, the use of sprinkler systems is mandated for certain types of tunnels and traffic volume. In Australia, the installation is not mandatory but new tunnels are routinely equipped with sprinkler systems [29].

For tunnels with fixed fire suppression systems, more research is necessary for the development of effective firefighting operations. Based on the findings from the research, desirable operations should be developed and proposed.

7 Application of the results

7.1 Development of Fire Scenario Curves for firefighting strategies

In section 3, previous road tunnel fires were analyzed focusing on the conditions of the initial ignition, i.e. single (IC1 and IC2) or collision incidents and the fire spread (IC3 and IC4). Based on this analysis, four Fire Scenario Curves have been developed: scenario **Curve A**, **B**, **C** and **D**. Alternative curves have also been developed for **Curve A** and **Curve C**, i.e., scenario **Curve a** and **Curve c** (see Figure 7.1). The benefit of developing these Fire Scenario Curves is to enable fire brigades to find distinctive characteristics for each fire type and to establish relevant firefighting and rescue strategies and tactics.

As discussed in chapter 3, fires which are started by collision of large vehicles develop so fast that unless the fire brigade quickly intervenes, the fire will develop rapidly. The fires can only be controlled in the early stage. Further, if more than one HGV is involved in the collision, subsequent fires can easily develop past the capacity of an average fire brigade and the possibility of fire spread is high. In the case of single fires, which start by a mechanical failure of the vehicles, growth is significantly slower than for collision fires. As described in Figure 7.1 when an HGV is involved and the intervention by fire brigade does not start until after the fire spread to neighbouring vehicles, single fires can also develop into catastrophic fires. Based on the characteristics of each type of a fire, simplified fire curves were developed as shown in Figure 7.1 and Table 7.1.

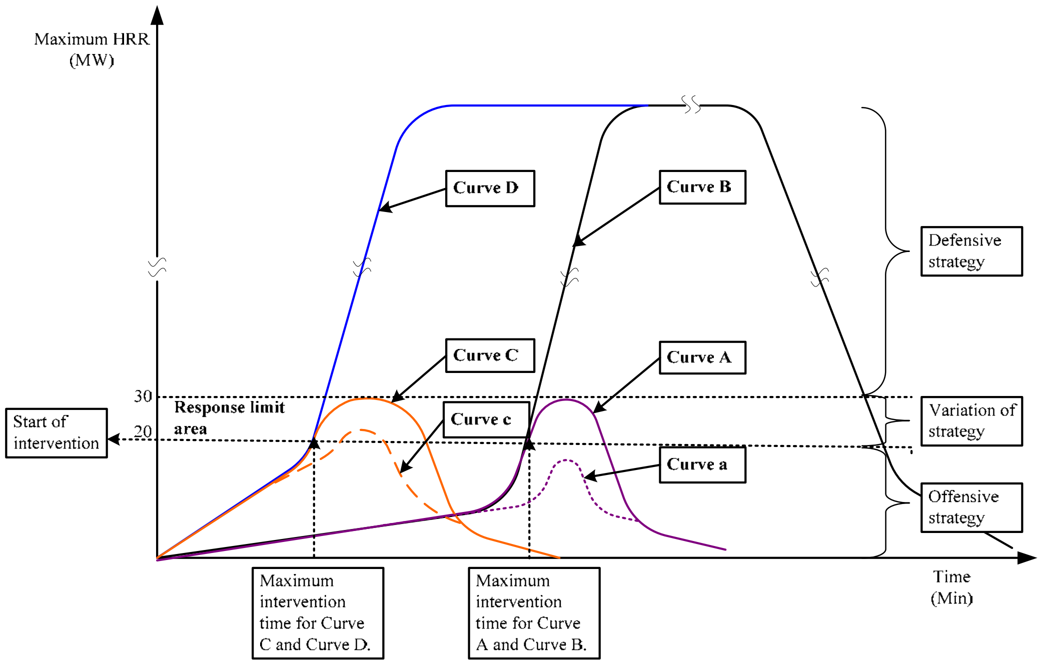


Figure 7.1 **Fire Scenario Curves for firefighting strategies.**

Table 7.1 Explanation of fire scenarios curves for firefighting strategies.

Fire Scenario Curve	Fire characteristic	Incident Category (see Table 3.2)	Energy potential	Typical Example
A	**Single** (slowly-developing) fires and fire spread is prevented by fire brigade or tunnel users. Intervention of fire brigade is vital.	IC1, IC2	Peak HRR do not pass the response limit. Peak HRR decreases by intervention of fire brigade	Mont blanc tunnel fire (1990)
a	**Single** (slowly-developing) fires but no possibility to fire spread. Intervention of fire brigade is always not necessary.	IC1	Peak HRR is too low to initiate a fire to spread and below the response limit.	Most of minor fires.
B	**Single** (slowly-developing) fires and fire spread	IC2	Peak HRR passes over the response limit before the intervention of fire brigade.	Mont blanc tunnel fire (1999)
C	**Collision** (fast-developing) fires but no fire spread	IC3	Peak HRR is not high for fire spread or decreases by the intervention of fire brigade.	Pfänder tunnel fire (1995)
c	**Collision** (fast-developing) fires but no possibility to fire spread. Intervention of fire brigade is always not necessary.	IC3	Peak HRR is too low to initiate a fire to spread and below the response limit.	Fløyfjell tunnel fire (2003)
D	**Collision** (fast-developing) fires and fire spread.	IC4	Due to the fire spread, energy potential increases heavily with fast pace enough to maintain continual fire spread.	Tauern tunnel fire (1999) and St. Gottard tunnel fire (2001)

Figure 7.1 above shows clearly that Fire Scenario **Curve C** and **Curve D** should be intervened within a short response time to prevent fire spread. However, **Curve A** and **Curve B** fires allow more time for the fire brigade to intervene. Fire Scenario **Curve a** and **Curve c** are not expected to become serious (i.e., develop into a catastrophic fire) regardless of intervention of the fire brigade because they can be extinguished by passengers and do not raise serious problems regarding fire spread and rescue.

It is also shown in Figure 7.1 what types of firefighting strategies should be applied. When the initial response fails due to the fact that the fire brigade arrives after the maximum intervention time or due to shortage of resources so that the fire is beyond the response limit, defensive strategies are effective which includes stopping fire spread in a certain area, decrease of the temperature inside tunnel, removal of smoke and toxic gases and access to the fire origin. When defensive operations are achieved successfully, the peak HRR will eventually drop down to the response limit. At this point, it is time to convert into offensive strategies. This means that large amount of resources are sent to the fire location for direct attack of the fire.

For the fire brigade, the main interest is to find out the 'intervention time' for each type of fire. However, there is too little information on the response time of fire brigades. The history of previous fire incidents of road tunnels in Appendix 1 was examined to determine a rough intervention time. Only a few testimonies concerning response time of the fire brigade were found. The summary of information is presented in Table 7.2.

Table 7.2 Response time of fire brigade

Year	Tunnel	Vehicle where fire occurred	Type of incident	Fire brigade response
2003	Fløyfjell	A car	Collision (wall) and fire. No fire spread (IC1).	Fire brigade arrived after **6 min** and quickly extinguished the car fire.
2001	St. Gotthard	2 HGV, one carrying a load of rubber tyres	Collision and fire. Fuel spill. Fire spread (IC4).	Fire brigade could access up to **15 - 20 m, 7 min** (after the collision) confined fire and finally extinguish the fire.
1999	Mont Blanc	A lorry with flour and margarine	Oil leakage and single fire. Fire Spread (IC2).	A patrolman could approach about **10 m, 13 min** (after the first alarm) but had to retreat due to heat and smoke.
1990	Mont Blanc	An HGV with 20 tons cotton	Single fire (IC1)	The French firefighters arrived **within 10 min**. They were able to control the blaze and extinguish it.
1986	Herzogberg	An HGV	Single fire (IC1)	Although the fire brigade took **over 20 min** to arrive, the fire was extinguished quickly.
1976	San Bernardino	A bus carrying 33 passengers	Single fire (IC1)	Rescue operation started **4 min** after the alarm. The fire did not spread

According to this limited information, the Swiss fire brigade could approach to within 15 – 20 m from the fire in St. Gotthard tunnel fire in 2001, 7 min after the collision and finally extinguish the fire. The fire was caused by a collision between HGVs and was expected to develop very fast due to the fuel spill. Based on this, the maximum intervention time can for a time being said to be around 7 min. In the Mont Blanc tunnel fire in 1999, it is reported that the fire was accessible up to 10 m after 13 min by a patrolman. Although the fire developed into a catastrophic fire, the fire could be controlled if appropriate preparations were made at this distance and at this time. The fire is designated as a single one by the analysis of section 3 and was developed very fast after a "delay time". A fire in the Herzogberg tunnel in 1986 is also a single fire involving a HGV. It is reported that it took over 20 min for fire brigade to arrive but the fire was extinguished quickly. For the two single fires above, the maximum intervention time can be said to be approximately 13 min for Mont Blanc tunnel fire and 20 min for the Herzogberg tunnel fire. As the analysis is based on insufficient knowledge taken from a few brief incident reports, it is recommended that suggested maximum response time described above should be regarded as a starting point for development of more sophisticated standards.

In conclusion, offensive strategies may be appropriate when it is expected that the first response units are able to start firefighting operations within a very short time. The time is 7 minutes based on the collision in St. Gotthard tunnel fire in 2001. For single fire incidents involving only one HGV, the maximum intervention time is 13 minute after the first alarm in Mont Blanc tunnel fire (1999) and 20 minute Herzogberg tunnel fire (1986). If the first response unit arrives after this time, defensive strategies should be the starting point for tunnel fire incidents.

7.2 Road Tunnel Classification models for preparation of fire operations.

In this section, classification models for road tunnels are proposed. The purpose of developing classification models is to diagnose the risk status of each road tunnel from the fire brigade's point of view and to determine the proper solution to decrease the risk level. For example, when a tunnel is proven to have a high risk of a fire and plays an important role in transportation, countermeasures such as installation of fixed fire suppression systems can be considered to decrease the risk levels. Four parameters are employed: passage of HGV and vehicles carrying dangerous goods, geometry of the tunnel, risk of congestion and the response time from the responsible fire station. The reason for selection of four parameters is explained as follows;

- **Passage of HGV and vehicles carrying dangerous goods:** The incident analyses in section 3 show that fires involving only cars and/or buses did not spread to neighbouring vehicles and they did not become the catastrophic fires which lead to huge loss of lives or property.

- **Type of the tunnel:** Road tunnel incidents shows that the possibilities of occurrence of collision fires and fire spreads are higher in bi-directional tunnels than in mono-directional tunnels. Further, fires in bi-directional tunnels are expected to yield a substantial number of evacuating and trapped passengers and therefore force fire brigades to focus their efforts on rescue operations in the early stages of an event, rather than firefighting, resulting in growing intensity of the fire.

- **Risk of congestion:** Congested tunnels lead to many problems for tunnel users and fire services. Tunnel users on either side of the vehicle in a fire will be faced with smoke and dangerous gases during their escape. Congestion of the tunnel makes it difficult for the fire brigade to arrive at the vicinity of the fire and forces them to focus on search or rescue, rather than firefighting, which could lead to an increased fire. The decision criterion on the congestion level is up to the fire brigade having the jurisdiction of the tunnels.

- **Response time:** Even though maximum intervention time is one of the crucial factors to determine the risk levels when fire brigades are involved in fire incidents, little has been known until now. Based on the examples of maximum intervention time for a few fires, i.e., fires in Mont Blanc tunnel, St. Gotthard tunnel and Herzogberg tunnel shown in section of 7.1, three time-periods are determined: within 8 min, 8–20 min and more than 20 min.

Proposed classification models of road tunnels for firefighting and flow chart for classification models of road tunnels are shown in Table 7.3 and Figure 7.2.

Table 7.3 Classification models of road tunnels for firefighting.

Class	**Description**	**Response time (min)**	**Example of Incident Category (see Table 3.2)**	**Example of fire scenario Curve (see figure 7.1)**	**Example of tunnels**
Class I	The passage of HGV and flammable vehicles carrying dangerous goods is restricted. On the view of fire spread, there is little risk. The tunnels are regarded as the safest tunnels.	Fire brigade may be able to extinguish the fire regardless of response time and the size of the fire.	IC1	A, a	Some urban tunnels only for cars and buses.
Class II	The uni-directional tunnels that are within 8 min time distance from the fire stations or where fixed fire suppression systems like sprinkler are installed. All types of fires may be under control either by fire brigades or fixed fire suppression systems.	Less than or equal to 8 minutes	IC1,IC2, IC3,IC4	A, a, C, c	Fløyfjell tunnel in Norway (sprinkler system) or urban tunnels with high fire load.
Class III	The uni-directional tunnels. Fire brigade may be able to extinguish slow-developed fires such as IC2, resulting in IC1 fires.	**Between 8 to 20 minutes**	IC1, IC2	A, a, C, c	Guadarram in Spain (20 min distance)
Class IV	Tunnels that are congested or bi-directional. The possibilities of occurrence of single fire or collision fires and fire spreads are expected to be significantly high.	**More than 20 minutes**	IC2, IC4	B, D	Bi-directional tunnels: Mont Blanc, Tauern, St. Gotthard tunnel.

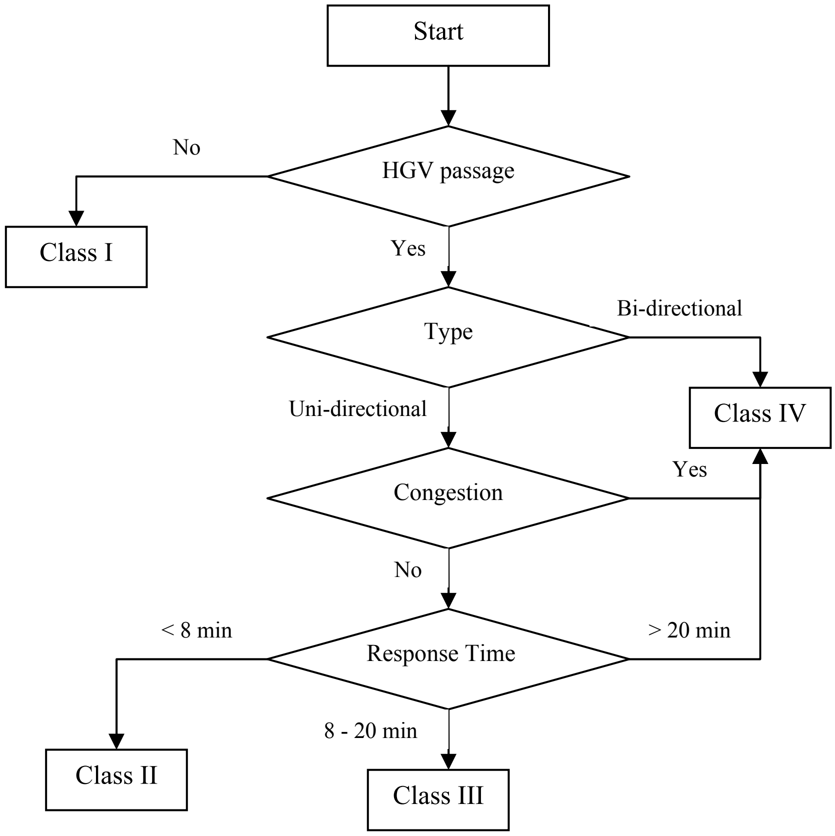


Figure 7.2 Flow chart for classification models of road tunnels

8 Discussion

Several key elements for effective operations of fire brigade in road tunnels have been examined and discussed under various environments for road tunnels. The elements and the situations were selected and considered to be applicable to any tunnels in the world and to give a general idea of how to improve the planning of fire fighting in road tunnels. However, no two tunnels typically have the exact same geometry, traffic flow or technical fire safety standards. Every tunnel has its own geographic or environmental characteristics. It is the responsibility of the local fire and rescue services to develop specific operational procedures for each tunnel. The information and fire operational proposals presented in this study can provide better ideas for setting up the fire and rescue plans in support of tactic procedures. The following list can facilitate the planning of the operational procedures by providing a list of issues that should be considered and solve (wherever possible) prior to an incident:

a. Apparatus and equipment
- Breathing apparatus: what types and what capacity are necessary for firefighting and rescue works?
- Nozzle type: what types of nozzles, jet or spray, should be employed for each operation?
- Optimum pressure and volume per minute of discharging water
- What extinguishing agent is effective for fires in tunnels, e.g. water or foam?

b. Firefighting personnel
- Staffing of the first arriving units and, if necessary, rescue teams.
- Staffing of supporting units such as ventilation and water-supply units.

c. Water supply
- How much water is required to extinguish different types of fires?
- How can an adequate water supply be obtained?
- How can required water be relayed to the fire site?

d. Location of fire and rescue services
- Organization of first response teams at each portal.
- Distance between public fire brigade and the both ends of the tunnels.

e. Tactical positioning
- The position of the first and later arriving fire units.
- Hose placement of initial and back-up lines.

Some of the considerations above are not well studied, so more research is needed on these issues. It is hoped that this study will inspire fire authorities to pay more attention to various issues regarding firefighting and rescue operations in road tunnels, and make the need for more efforts in solving presently unsolved problems.

It seems strange that when risk analysis on the design stage of a new tunnel is carried out, considerations on the response capacities of fire and rescue services having the jurisdiction (such as distance between fire stations and the tunnel, and the number of firefighters and fire engines available) are not included in the risk analysis process. For that reason, the classification models of road tunnels that is proposed in chapter 7.2, can be of great assistance. The capacity of the fire response unit for each category of tunnel has not been proposed but is something which should be dealt with in future research projects. The proposed classification model is based on four parameters: passage of an HGV and vehicles carrying dangerous goods, type of tunnel, risk of congestion, and response time, where the response time is the most crucial parameter for firefighting and rescue operations.

It should be noted that the study has focused on fire brigades and outlines the potential risk levels which each road tunnel may have. The study may assist fire authorities or stakeholders to develop countermeasures to compensate for any potential danger. It is hoped that more advanced parameters can be developed which represent the contribution of the fire and rescue work to the risk evaluation and are included into the future risk analysis process.

9 Conclusions

Basic operational elements consisting of effective firefighting operations in road tunnels are discussed. The response time of average fire units and the maximum intervention time for various scenarios of fires are given in order to determine subsequent operations. It is found that an average fire unit manages to control a fire which starts in an HGV but does not involve a trailer. It can manage fires that are in the range of 20 – 30 MW HRR when the active firefighting operation starts rapidly. This implies that a fire occurring in passenger cars, buses or both can be managed by the first fire units arriving. In the case of maximum intervention time, limited information is available. There is still a need for more research into this topic. Based on the very limited information available, it is argued that collision fires should be fought within 7 minutes and single fires should be tackled somewhere between 13 – 20 minutes in order to ensure control the initial fire and avoidance of a catastrophic outcome. Depending on two criteria i.e. response limit and maximum response time, appropriate strategies should be selected which determine other operational procedures such as access routes and the direction of air flow from ventilation systems.

In addition to the proposal for effective firefighting operations, three models were developed and discussed to explain how findings and proposals in this study can be applied and used, i.e.:

- Incident Categories (IC1, IC2, IC3, IC4),
- Fire Scenario Curves (A, a, B, C, c, D, E), and
- a Road Tunnel Classification Model (I, II, III, IV).

Incident Categories indicate the type of initial incident, Fire Scenario Curves were developed to show the relationship between strategies, response limit, maximum intervention time and types of fires. Road Tunnel Classification models can be useful when a fire brigade evaluates fire risk levels in the tunnels under its jurisdiction from the firefighting point of view and sets up preventive measures.

The aim of this study was to provide general information concerning effective operational procedures in road tunnels, not to give specific tactical procedures which can be applicable for all types of road tunnels. It is the responsibility of national or local fire authorities to develop specific response manuals and plans applicable for each road tunnel under their jurisdiction. It is hoped that this study can be a reference document for the development of such tactics and contingency plans and initiate discussion and research on fire brigade operations in tunnels.

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Appendix 1 A history of fire incidents in road tunnels

Duration is given in hours if nothing else is specified.

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
2006	Viamala Switzerland (0.742)	NA	Car+bus	Front collision between a car and a bus.	NA	Collision and fire. No Fire spread.	9 dead. 5 injured.	1 bus 2 cars	NA	NA	–	**C**	Internet website: http://www.swissinfo.org/
2005	Frejus France/ Italy (12.9)	Bi-directional	A HGV carrying tyres	Engine fire	6	Single fire. Fire spread.	2 dead. 21 treated for smoke inhalation	4 lorries 3 fire fighting vehicles.	Serious damage. Tunnel closed.	Fire extinguished before it reached glue load in 4th lorry	1. load:Tyres 2.load:Cheese 3.load:scrap (2 dead) 4.load:glue	**B**	Internet website: http://www.swissinfo.org/
2004	Frejus France/ Italy (12.9)	Bi-directional	A HGV	Braking system	NA	Single fire	0	1 HGV	Closed for about 2.5 hours	The fire was extinguished easily	_	**A**	[4]
2004	Cointe Belgium (1.3)	NA	A HGV	NA	NA	Single fire	0	1 HGV	Closed for a few days	NA	_	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
2004	Dullin France (1.5)	NA	A coach carring 37 tourists	Engine compartment	NA	Single fire	0	1 coach	NA	NA	The coach managed to escape out of the tunnel while the vehicle was on fire.	**A**	[4]
2003	Golovec Slovenia (0.7)	NA	A bus carrying 50 volunteer fire-fighters	NA	NA	Single fire	0	1 bus	NA	NA	The fire was extinguished by the passengers with portable extinguishers	**A**	[4]
2003	Fløyfjell Norway (3.1)	NA	A car	Collision with wall and fire	NA	Collision (wall) and fire. No fire spread.	1 dead	1 car	NA	Fire brigade arrived after 6 min. and quickly extinguished the car fire.	The tunnel has sprinklers system. The driver of the car was trapped in his vehicle because of the crash and died in the fire	**C**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
2003	Locica Slovenia (0.8)	NA	A HGV carring a cargo of aluminium beams	NA	NA	Single fire	0	The cab and canvas.	NA	The fire brigade extinguished the fire on arrival.	_	**A**	[4]
2002	Homer New Zealand	NA	A coach carring 32 tourists	Motor	NA	Single fire	3 injured	1 coach	NA	NA	_	**A**	[4]
2002	Ted Williams USA (2.6)	NA	A bus transporting baseball players	Electrical compartment	NA	Single fire	Some injured	1 bus	NA	NA	The driver of the bus and several of the players were treated for smoke inhalation	**A**	[4]
2002	Tauern Austria (6.4)	Bi-directional	A lorry	A faulty engine	NA	Single fire	0	1 lorry	NA	The fire brigade were able to bring the fire under control very quickly	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
2001	Gleinalm(3 September) Austria (8.3)	Bi-directional	A tourist coach	NA	NA	Single fire	0	1 coach	NA	NA	_	**A**	[4]
2001	Gleinalm (29 July) Austria (8.3)	Bi-directional	A coach	Engine compartment	NA	Single fire	0	1 coach	NA	NA	The driver was able to drive the coach out into the open air before stopping	**A**	[4]
2001	Gleinalm (7 August) Austria (8.3)	Bi-directional	A car	Front collision between a lorry and a car	2 h	Collision and fire. No Fire spread.	5 dead 4 injured	1 lorry and 1 car	NA	The fire was successfully extinguished by the fire brigade shortly	–	**C**	[5]
2001	St. Gotthard Switzerland (16.9)	Bi-directional	2 HGV, one carrying a load of rubber tyres	A head on collision between 2 lorries.	2 days	Collision and fire. Fuel spill. Fire spread.	11 dead	13 lorries, 4 vans, 6 cars	Closed 2 months. Collapse of over 250 m of the tunnel linning	NA	_	**D**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
2001	Prapontin Italy (4.4)	Uni-directional	A HGV	Mechanical problem	NA	Single fire	19 injured	1 HGV	Closed for about 9 days	NA	–	**A**	Internet website: http://www.swissinfo.org/
2001	Tauern Austria (6.4)	Bi-directional	2 cars	a head on collision	NA	Collision and fire. No fire spread.	0	2 cars	NA	NA	The fire was extinguished quickly by the driver of one of the cars	**C**	[4]
2000	Laerdal Norway (24.5)	NA	A bus transporting about 50 passengers	NA	NA	Single fire	0	1 bus	NA	NA	The fire was small and was easily dealt with by the bus driver	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
2000	Seljestad Norway (1.3)	NA	The trailer-truck with diesel fire in the engine room before the collision.	Front-rear-collision 1 truck, 4 cars	45 min.	Collision and fire. Fire spread.	6injured	1 lorry, 6 cars, 1 MC	Serious damage. Closed 1 and 1/2 days	The fire brigade arrived within 30 minutes.	Due to the prevailing wind there was breathable air in the tunnel and the fire brigade were able to approach the scene of the fire easily. The fire spread to involve all the vehicles within minutes.	**D**	[5]
2000	Oslofjord Norway	NA	A lorry	NA	NA	Single fire	0	1 lorry	NA	NA	Minor fire occurred	**A**	[4]
2000	Saukopf Germany (2.7)	NA	A car	NA	NA	Single fire	0	1 car	NA	The fire brigade extinguished the fire easily	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
2000	Rotsethhorn Norway (1.2)	NA	NA	A collision and subsequent fire	NA	Collision and fire. Fire spread not known.	2 dead	NA	NA	NA	–	**NA**	[4]
2000	Cross-harbour Hong Kong	NA	A car	NA	0.5	Single fire	0	1 car	NA	The first emergency response arrived within 3 minutes. But they were unable to control fire fire. The fire brigade arrived 2 minutes later.	–	**A**	[4]
2000	Tauern Austria (6.4)	Bi-directional	A HGV	NA	0.5	Single fire	0	1 HGV	NA	This fire was dealt with rapidly and was extinguished within half an hour by fire-fighters on	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
										both sides of the vehicle			
1999	Candid Germany (0.252)	NA	A car	Engine compartment	NA	Single fire	0	1 car	NA	Due to the volume of traffic, the fire brigade took a long time to reach the fire, but on arrival the fire was quickly extinguished	–	**A**	[4]
1999	Tauern Austria (6.4)	Bi-directional	A lorry with a cargo of spray cans inclding paints	Front-rear-collision between 4 cars and 2 lorries.	15 h	Collision and fire. Fuel spill. Fire spread.	12 dead, 49 injured	14 lorries and 26 cars	Serious demage	NA	8 people died as a direct result of the crash	**D**	[5]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
1999	Mont Blanc France/ Italy (11.6)	Bi-directional	A lorry with flour and margarine	Diesel fuel leaking onto hot surfaces of engine compartment	53	Oil leakage and fire. Fire spread.	39 dead	23 lorries, 10 cars, 1 motor cycle	Serious damage. Reopen in 2001.	NA	Poor operation of the ventilation system and lack of communication between the French and Italian operators	**B**	[5]
1998	Gleinalm Austria (8)	NA	A double deck coach	a short circuit	Not Kwown	Single fire	0	1 coach	NA	NA	The fire spread to one of the fire-fighting vehicles	**A**	[4]
1997	St. Gotthard (17 September) Switzerland (16.9)	Bi-directional	A bus	engine overheating	0.2	Single fire	0	1 bus	NA	NA	_	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
1997	St. Gotthard (31 October) Switzerland (16.9)	Bi-directional	1 HGV loaded with cars	Fire in engine	1.2	Single fire	1 injured	1 HGV	serious damage 100 m	NA	–	**A**	[4]
1997	PrapontinItaly (4.9)	NA	A HGV transporting textiles	Brakes overheating	4	Single fire	5 Injured	1 HGV	NA	The fire brigade were on the scene within 5 minutes. Fire-fighting was hindered by thick smoke, high temperatures, explosive spalling of the concrete lining, inappropriate use of the ventilation system and a lack of water in the	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
										hydrants.			
1996	NA	NA	A bus	Engine	2	Single fire	0	1 bus	NA	NA	_	**A**	[5]
1996	Isola delle Femmine Italy (0.148)	NA	1 tanker with liquid gas + 1 small bus	Front-rear-collision	NA	Collision and fire. 2 times exposion. Fire spread.	5 dead and 20injured	1 tanker 1 bus 18 cars.	Serious damage. Tunnel closed for 2.5 days	NA	_	**D**	[5]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
1995	Pfänder Austria (6.7)	Bi-directional	A lorry with trailer	a head on collision between a lorry and a minibus.	1	Collision and fire. No fire spread.	3* dead, 4 injured	1 lorry, 1 van, 1 car	Serious damage	Smoke hindered the fire brigade	* As a result of crash	**C**	Internet website: http://www.swissinfo.org/
1996	Hitra Norway (5.6)	Bi-directional	A mobile crane	Motor	2	Single fire	0	1 mobile crane	NA	NA	_	**A**	[4]
1994	St. Gotthard Switzerland (16.9)	Bi-directional	A HGV carrying 750 bicycles	a tyre	2	Single fire	0	1 HGV	There was significant damage to 50 m of the tunnel lining	NA	_	**A**	[4]
1994	Castellar France (0.57)	NA	A lorry carrying water paper	an exploding tyre	NA	Single fire	0	1 lorry	NA	NA	_	**A**	[4]
1994	KingswayUK (2)	Uni-directional	A bus	Engine room	1	Single fire	0	1 bus	Minor damage	NA	The fire was extinguised by the large powder extinguishers	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
1994	Huguenot South Africa (4)	NA	A bus with 45 passengers	Gearbox	1	Single fire	1 dead, 28 injured	1 bus	Reopened 4 days later	Ther fire brigade arrived at the scene within 12 minutes of the first alarm	The fire was relatively small and could have been extinguished by fire extinguishers , however this was not done and the fire grew, killed the bus driver	**A**	[5]
1993	Frejus France/ Italy (12.9)	Bi-directional	1 HGV	Engine fire	2	Single fire	0	1 HGV	NA	NA	_	**A**	[4]
1993	Hovden Norway (1.3)	NA	A motor cycle and 2 cars	Front -rear-collision	1	Collision and fire. No Fire spread.	5* injured	1 motor cycle and 2 cars	111 m insulation material damaged.	NA	* As a result of crash	**C**	[5]
1993	Serra a Ripoli Italy (0.442)	NA	1 car and 1 lorry with rolls of paper	Collision	2.5	Collision and fire. Fire spread.	4 dead and 4 injured	5 lorries, 11 cars	Little damage	NA	_	**D**	[5]

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1990	Røldal Norway (4.7)	NA	A vehicle transporter	Engine overheating	50 min.	Single fire	1 injured		Little damage	NA	–	**A**	[5]
1990	Mont Blanc France/ Italy (11.6)	Bi-directional	A HGV with 20 tons cotton	Motor	NA	Single fire	2 injured	1 lorry	Some equipment destroyed	The French fire fighters arrived within 10 minutes. Despite the fact that the fire had spread to involve the entire vehicle by this point, the fire fighters are able to control the blaze and extinguish it	–	**A**	[5]
1988	Mont Blanc France/Italy (11.6)	Bi-directional	A HGV	NA	NA	Single fire	0	1 HGV	NA	The French fire-fighters were able to extinguish the fire on arrival	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
							People	Vehicle	Structures or closure				
1987	Tanzenberg Austria (2.4)	NA	A car	A suicidal collision with the wall	NA	Collision and smoke. No flame	0	1 car	Significant damage	NA	–	**C**	[4]
	Gumefens Switzerland (0.343)	Uni-directional	A lorry with trailer	Front-rear-collision	2	Collision and fire. Fire spread.	2 dead, 3 injured *	2 lorries, 1 van, 5 cars	Slight damage	NA	* As a result of crash	**D**	[5]
1986	Herzogberg Austria (2)	NA	A HGV	Brakes overheating	NA	Single fire	0	1 HGV	Not Kwown	Although the fire brigade took over 20 minutes to arrive, the fire was extinguished quickly. The smoke and temperature conditions in the tunnel did not hinder the fire brigade's approach to the fire.	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scenario curves	Reference
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1986	L'arme France (1.1)	Uni-directional	A lorry with trailer	Collision between a lorry and a car	NA	Collision and fire. Fire spread.	3 dead , 5 injured	1 lorry and 4 cars	Some equipment destroyed	NA	–	**D**	[5]
1983	Pecorila Italy (0.662)	NA	A fish lorry	Fron-rear-collision	NA	Collision and fire. Fire spread.	9 dead, 22 injured	10 cars	Little damage	NA	–	**D**	[5]
1983	Frejus France/Italy (12.9)	Bi-directional	A HGV loaded with plastics	A gear box failure	2	Single fire	0	1 HGV	200 m of the tunnel lining was damaged	NA	–	**A**	[4]
1982	Salang Afghanistan	NA	At least one petrol truck	Unknow. Probably mine explosion	NA	Explosion and fire. Fire spread.	Exact number not known	At least one petrol truck	NA	NA	The number of fatalities vary from 176 to several thousand	**B**	[5]
1982	Caldecott USA (1)	Uni-directional	1 car, 1 coach, 1 petrol tanker	Front-rear-collision	2.4	Collision, fuel spill and fire. Fire spread.	7 dead, 2 injured.	3 lorrys, 1 coach, 4 cars	Serious damage over 580 m	NA	–	**D**	[5]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
1981	Mont Blanc France/Italy (11.6)	Bi-directional	A HGV	Engine compartment	NA	Only Smoke	0	1 HGV	Not Kwown	NA	Only thick smoke was observed	**A**	[4]
1980	Sakai Japan (0.459)	NA	A lorry	Collision	3	Collision and fire. Fire spread.	5 dead, 5 injured	10 vehicles	Not Kwown	NA	–	**D**	[4]
1980	Kajiwara Japan (0.74)	NA	A lorry with 3600 litres of paint in 200 cans	Collision with side wall and overturning	1.2	Collision and fire. Fire spread.	1 dead	2 lorrys(4 and 10 tons)	Serious damage over 280 m	NA	–	**D**	[5]
1979	Nihonzaka Japan (2)	Uni-directional	4 lorries, 2 cars	Front-rear-collision	159	Collision and fire. Fire spread.	7 dead, 1 injured	127 lorries, 46 cars	Serious damage over 1100 m	Traffic congestion lead to a delay in the arrival of the fire brigade and their fire fighting activities were cut off after only half an hour as the water tanks ran dry	–	**D**	[5]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
1978	Mont Blanc France/Italy (11.6)	Bi-directional	A HGV	NA	NA	Only Smoke	0	1 HGV	Not Kwown	NA	Only thick smoke was observed	**A**	[4]
1978	Velsen Netherlands (0.767)	Uni-directional	2 lorries, 4 cars	Front-rear-collision	1.2	Collision and fire. Fire spread.	5 dead* ,5 injured	2 lorries, 4 cars	Serious damage over 30 m	NA	* As a result of crash	**D**	Internet website: http://www.swissinfo.org/
1976	Porte d'Italie France (0.43)	NA	A HGV carrying 16 tons of polyester film	High speed. Engine.	1	Single fire	12 injured	1 HGV	150 m of the tunnel lining damaged	NA	–	**A**	Internet website: http://www.swissinfo.org/
1976	San Bernardino Switzerland(6.6)	Bi-directional	A bus carrying 33 passengers	Engine room overheating	NA	Single fire	0	1 bus	NA	Rescue operationg started 4 min. after the alarm. The fire brigade response was very fast, and the fire did not spread.	–	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
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1975	Guadarrama Spain (3.3)	Uni-directional	A tanker transporting pine resin	Gear box failure	2.45	Single fire	0	1 tanker	Damage to the facilities within 120 m	Fire brigade arrived in 20 min.	_	**A**	[4]
1974	Chesapeake bay USA	NA	A HGV	an exploding tyre.	4	Single fire	1 injured	1 HGV	NA	NA	The fire involved the fuel tank of the vehicle	**A**	[4]
1974	Mont Blanc France/ Italy (11.6)	Bi-directional	A lorry	Motor	15 min.	Single fire	1 injured	NA	NA	The French fire brigade was quick to arrive on the scene and despite thick smoke, was able to extinguish the fire quickly	_	**A**	[5]
1970	Wallace USA (1)	NA	A comper truck	Engine	NA	Single fire	0	1 comper truck	Little damage	NA	_	**A**	[4]

Year	Name Country Tunnel length (km)	Type of tunnel	Vehicle where fire occurred	Most possible cause or location of fire	Duration of fire	Type of accident	Consequences			Fire brigade response	Remark	Scena rio curves	Reference
							People	Vehicle	Structures or closure				
1968	Moorfleet Germany (0.243)	NA	A HGV carrying a load to 14 tons of polyethylene bags	Brakes overheating	1	Single fire	0	1 HGV	34 m of the tunnel lining	NA	_	**A**	[4]
1967	Suzaka Japan (0.244)	NA	A lorry*	Engine compartment	11	Single fire. Fire spread.	2 injured	13 trucks	NA	Due to inadequate operational procedures the fire spread to other trucks in the tunnel	*Loaded with about 600 polystyrene boxes and other combustible goods	**B**	[4]
1965	Blue Mountain USA (1.3)	NA	A HGV carrying fish oil	Motor	NA	Single fire	0	1 HGV	NA	NA	_	**A**	[4]
1949	Holland USA (2.6)	Uni-directional	A lorry with 11 tons of carbon disulfid	Load falling off lorry explosion	4	Explosion and fire. Fire spread.	66 injured	10 lorries, 13 cars	Serious damage over 200 m	NA	_	**B**	[5]

NA = Information Not Available

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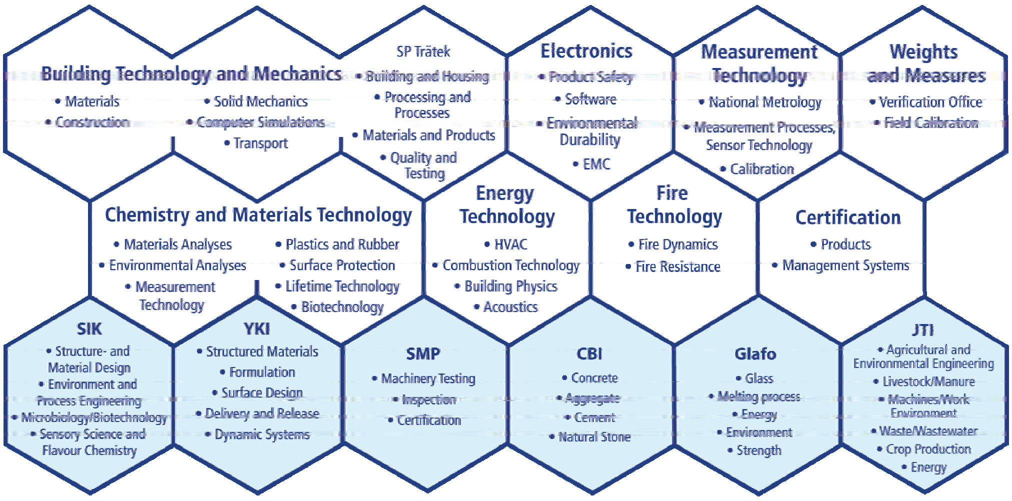

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