Chapter 1
Introduction

Abstract An introduction to the main differences between open fires, building fires and tunnel fires is given as the basis for better insight into the physics of fires in tunnels. An overview is given of what type of fires is to be expected in different types of tunnels and what consequences such fires may have. A short description of mitigation systems commonly used to increase the fire safety in tunnels is also given and their main features are put into the context of fire dynamics. Finally, the major fire incidents that have occurred are summarized and analysed in order to understand the main reasons for their different consequences.

1.1 Introduction

The main purpose of this book is to provide a sound understanding of fire dynamics in tunnels. The word "tunnels" is broadly used to mean road tunnels, rail tunnels, metro tunnels, mines or tunnels during construction. The book aims to improve knowledge on fire physics and thereby facilitate understanding of this physics for practicing engineers and researchers. It is important to state now that there is no large difference in the fire physics describing these types of tunnels, independent of their use or complexity. Parameters such as length and cross-sectional geometry are important, but the vehicles that burn inside these different tunnels and the mitigation systems that are applied as well as construction protection adopted are also important.

Fire dynamics usually relates to fire behaviour in ordinary sized compartments (rooms) or corridors. The knowledge of fire chemistry and fire dynamics is treated either with or without the direct interaction of the compartment and the ventilation conditions. Much of the fire research to date has been carried out either inside a normal-sized building compartment or in a building with a large volume (For example, fire laboratory) where one can assume no interaction of the environment with the fire plume (open fire). Some research has also been carried out on outdoor fires, where an external wind potentially has a strong effect.

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Most of the fundamental research on fire dynamics in tunnels is focused on smoke spread in tunnels with low ceiling heights and on fire development in single burning vehicles. The requirement for the ventilation systems to prevent back-layering of smoke, that is, the critical velocity, is the single most investigated parameter in tunnel fire research [1]. Combining the knowledge on fire dynamics in buildings and that in tunnels is a challenge, as there are major differences that cannot readily by explained for both types of constructions. In many cases, this creates confusion that is difficult to resolve. One such example is the misconception or misunderstanding that is present concerning well-ventilated fires and under-ventilated fires in tunnels and buildings. The basic phenomena for these terms are explained in detail in Chap. 2 in this book.

The influence of ventilation on heat release rates (HRRs) in vehicle fires and how the smoke, toxic gases and heat spread in the tunnel is very important to understand. This is apparent owing to the occurrence of many disastrous tunnel fires in the past two decades. Thus, in order to determine an appropriate design fire for a fire safety system in a tunnel, some understanding on fire development in vehicle fires and how the fire interacts with its environment is required.

The research carried out in ordinary compartments or corridors, in large laboratory buildings and outdoor (open fires) is of great value and it is important that it be used as a platform in tunnel fire research. Therefore, it is crucial to have a good understanding on the main differences between these different types of fires.

1.2 Characteristics of Tunnel Fires

Tunnel fires differ in many aspects from open fires and building fires. Open fire is defined here as a fire without any interaction with its surrounding geometry or enclosure. This can be the case for a fire outside a building in a quiescent environment or inside a building that is sufficiently large that the fire is not directly affected by its presence. A fire outside a building that is exposed to strong external wind is not considered here.

According to this definition, there are at least two important ways in which tunnel fires differ from the open fires [2], that is, in terms of:

- The heat feedback from the surrounding environment
- The effect of natural ventilation on the fire

The heat feedback to the fuel surface in open fires is governed by the flame volume. In tunnel fires it is the same, except that additional parameters such as tunnel lining, cross-sectional area and ventilation also play an important role.

The oxygen needed for combustion is not always readily available in tunnels in the same way as in the open (where full access can always be assumed). The conditions may either develop to a well-ventilated fire (fuel-controlled) where unreacted air by-passes the burning vehicles, or under-ventilated fire (ventilation-controlled) giving rise to large amounts of toxic fume and products of incomplete combustion.

A fire that develops in a tunnel interacts with the ventilation airflow and generates complicated air flow patterns and turbulence in the vicinity of the fire. The heat generated by the fire warms up the surrounding air, and in the case of a slope inside the tunnel, buoyancy forces are created along the tunnel which could govern the movement of the air flow inside the tunnel. This may lead to drastic changes in the ventilation flow pattern for the whole tunnel system. If the resulting longitudinal flow velocity is not high enough, a reverse flow of hot gases in the ceiling will be created. This phenomenon is better known as back-layering. In order to prevent any type of back-layering, the longitudinal velocity inside the tunnel has to be higher than a critical value. Usually, this critical value is about 3–3.5 m/s for most tunnels. The main problem with natural ventilation in tunnels is that not only the tunnel geometry, the size and the location of the fire govern the flow of hot gases in the tunnel, but also winds and atmospheric conditions outside the portals may have a strong influence on the ventilation system.

The complexity in understanding what is happening inside a tunnel is difficult for the rescue personnel such as firefighters who have to deal with the situation while the fire is developing. The smoke can only be visual from portals, so the decision to attack the fire can only be based on which portal the smoke exits unless a closed-circuit television (CCTV) system exists. Effects of the fire on the natural ventilation inside the tunnel not only complicate firefighting procedures but also present extreme hazards by rapidly propagating toxic fumes and gases far away from the fire. Sudden changes in the air flow could easily occur due to pressure changes inside and outside the tunnel portals. This situation can only be controlled when mechanical systems are applied and the smoke management becomes much easier and a safer environment for evacuees and firefighters can be created in the case of a good ventilation design. In contrast, in building fires the firefighters can always observe the situation from a safe position outside the building. According to Ingason [2], tunnel fires differ from building compartment fires in at least three important ways, that is, in terms of:

- The effects of the *ventilation factor*
- The *flashover* conditions
- The *stratification* development

The maximum HRR in compartment fires is usually dictated by the ventilation factor. The ventilation factor is a parameter defined by the opening areas and height of the openings of the compartment, see Chap. 2 for detailed information. In tunnels the situation is entirely different. The size of the fire and its position within the tunnel, the slope of the tunnel in the vicinity of the fire, the cross-sectional area where the fire takes place, the total length of tunnel, the type of the tunnel lining material (concrete, blasted rock) and the meteorological conditions at the entrance and exit are the parameters that govern the natural ventilation within the tunnel system. This means that tunnels work more or less like communicating vessels. The results of this is that the excess air available for combustion is an order of magnitude higher than in compartment fires which are governed by the ventilation factor. Tunnels are also often equipped with mechanical ventilation which is sometimes termed forced ventilation. The mechanical ventilation consists of supply/exhaust fans and/or jet fans in the ceiling. In Chap. 13, these ventilation systems are presented more thoroughly. The consequence of using mechanical ventilation is mainly seen in terms of the combustion efficiency, spread of heat and smoke as well as the HRR in tunnels. These ventilation conditions differ significantly from compartment fires which are usually naturally ventilated through windows or other openings. There are many buildings equipped with mechanical ventilation but the flow rate is relatively small as compared to the fire size, and usually when a fire becomes fully developed the windows break and the fire becomes dominated by the ventilation.

In very long tunnel tunnels with natural ventilation and nearly no slope, over several kilometres, it can be shown that the natural flow inside a tunnel and towards the fire source may be predicted by the ventilation factor at the portals (cross-sectional area times the square root of the height). This has not been experimentally verified but theoretical investigations by the authors show that this may be the case. This means that previous thinking about how natural ventilation is governed in very long tunnels with nearly no slope needs to be reconsidered. Generally, the smoke flow descends to the floor level after travelling a certain distance. Then the smoke flow could approximately be considered as being fully mixed, but still there exists indistinct layers, that is: a lower layer with incoming fresh air (partly vitiated) and an upper layer with outgoing combustion products.

Flashover is defined as the rapid transition to a state such that all the surfaces of the combustible materials within a compartment are involved in the combustion. Fires in compartments can easily grow to ‘flashover’ within a few minutes. Flashover is not expected to take place outside a confined space such as a compartment. The volume of the compartment is very important as is the composition of the materials found in the compartment together with the opening sizes. Tunnel fires, in that sense meaning fires in a long space with two large portal openings, are therefore not likely to grow to a conventional flashover. The main reason is due to large heat losses from the fire to the surrounding walls, lack of fuel in relation to the volume size and containment of hot fire gases. The flashover phenomenon is explained in details in Chap. 2.

Experiments and theoretical considerations show that flashover can easily occur in a train compartment or a truck cabin located inside a tunnel [3, 4], see Fig. 1.1. This type of flashover will not occur inside a tunnel space. In the same way, the risk of secondary deflagration due to under-ventilated fires is much lower in tunnels than in building compartment fires [2]. The main reason for this is the difference in the ventilation conditions as explained above and the geometry and heat losses to the surrounding tunnel walls. The amount of fuel load in relation to the tunnel volume also plays an important role.

Although flashover appears to be impossible in a tunnel fire, an under-ventilated fire in a tunnel is possible. This should be given special attention. In an under-ventilated fire, the consequences of the activation of a powerful ventilation system may be dramatic. The flame volume may suddenly increase in size and length, and the fire may easily spread forward due to the preheated vehicles downstream of the

Fig. 1.1 Initial stages of a "flashed over" situation in a metro train carriage. The flames start to plunge out from the broken windows and open doors. (photo Per Rohlén)

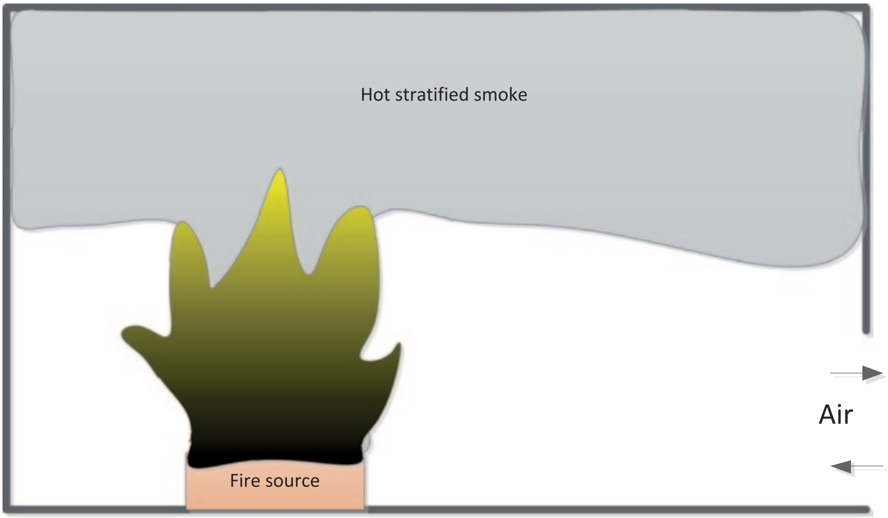

Fig. 1.2 The smoke stratification in the early stage of a compartment fire

fire, although this phenomenon cannot be defined as 'flashover' in the traditional sense of the word [2].

The stratification formation of the smoke layer differs from compartment fires. In the early stages of compartment fires, an upper quiescent buoyant smoke layer is formed with a cold smoke free layer below, see Fig. 1.2. Due to the confinement of the compartment, the smoke layer descends gradually to a level slightly lower than the upper edge of the door or windows. Therefore, at least in the early stage, the height of the openings governs the smoke layer height. However, this is not the case in a tunnel fire.

At a short distance from the point where the fire plume impinges on the tunnel ceiling, the smoke flow transits to a longitudinal flow on both sides in a tunnel

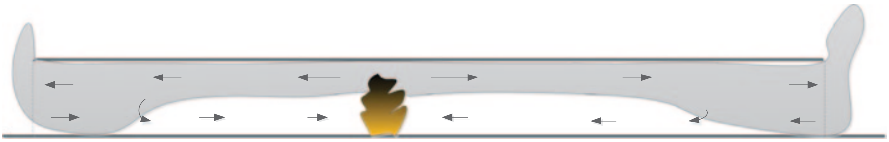

Fig. 1.3 The smoke stratification in a tunnel fire with low ventilation

with essentially no longitudinal ventilation and nearly no slope. Eventually such a layer will be become thicker and descend towards the tunnel floor, see Fig. 1.3. The distance from the fire when this may occur is dependent on the fire size, the tunnel type and the perimeter and height of the tunnel cross-section [2]. See Chap. 12 for further information concerning smoke stratification in tunnels.

If a longitudinal ventilation system is activated, this stratified layer will gradually disperse. At first on the upstream side of the fire, a smoke layer will still exist (back-layering). On the downstream side, the stratification of the smoke is gradually dispersed. This will be governed by the heat losses to the surrounding walls and by the turbulent mixing between the buoyant smoke layer and the opposite moving cold layer. The smoke stratification is important for those who have to escape from the tunnel. The characteristics of the smoke spread are highly dependent on the air velocity and location in the tunnel.

Despite the fact that the fire behaviour can be different depending on the envelope (tunnel, building or in the open) the measures to deal with it vary. Further, the fire load itself in a tunnel is very different from that in a building. The vehicles in tunnels are in most cases the only fuel that is available. In underground car parks, one may find some similarities, and much research has been conducted on car park fires which is very useful for tunnel fire research. In Chaps. 4 and 5, an overview of fire development in vehicles is given.

The mitigation methods (technical safety systems) to deal with tunnel fires vary. In the following section, a short overview of different mitigation methods is given. These systems are described in more details in different chapters in this book.

1.3 Mitigation Systems in Tunnels

A mitigation system is defined here as a technical system or a method to increase the safety during a fire. The systems that need some basic fire dynamic knowledge to design or handle are presented. These include the structural fire protection which relate to different boundary conditions such as the gas temperatures and heat fluxes, the ventilation systems, the evacuation systems which relates to different combustion products, visibility and tenability requirements in the smoke, and finally, detection and suppression systems.

The heat exposure as an input for calculation of the load bearing capacity is important. The main load is through heat flux from burning vehicles. The heat fluxes vary depending on the tunnel geometry, ventilation in the tunnel and the type and shape of the fire load. Although the heat flux in kilowatts per square meter (kW/m^2) is should be used for describing the heat exposure onto a tunnel construction, it is seldom applied as input into models for calculating temperature rises inside the structure. Instead different types of time–temperature curves are given and the boundary conditions are given as a lumped heat flow constant. The time–temperature curves are usually standardized fire curves (ISO 834 [5], HC [6], RWS [7] etc.), see Chap. 8, Sect. 1, and can vary depending on the guidelines used. In tunnels, the time–temperature curves are usually more severe than those used in buildings. This difference has to do with the dynamics of the combustion process. In well-ventilated tunnels with relatively low ceiling height, the maximum gas temperatures can easily reach a level of 1350 °C, whereas in buildings this is usually in the range of 900–1100 °C. The main reason for this is the difference in the ventilation conditions and thereby the heat flux exposure. The understanding of heat fluxes and temperature development is of great importance and is explained in more detail in Chaps. 8 and 10.

The ventilation system is one of the most important safety features in tunnels. It makes it possible to control the smoke spread and thereby influence the outcome of a fire incident. The mechanical systems can be controlled automatically or by persons in a control center for a specific tunnel or tunnels. In the early history of ventilation design (late sixties), the systems mainly consisted of smoke extraction systems that is, the smoke was exhausted out of the tunnels. The terminology for these types of systems is “semi-transverse” or “fully transverse” systems. “Semi-transverse” means that they only exhaust the smoke whereas “fully transverse” both supply fresh air along the tunnel and exhaust the smoke. Today, these systems have been optimized in the design and are termed point extraction systems. The tunnels in the Alps regions, especially those which have bidirectional traffic, are often equipped with point extraction systems but such systems are also found in other parts of the world. The smoke is not only controlled by extracting the smoke but also by the longitudinal flow created inside the tunnel. Additional jet fans in the ceiling have also be applied to control the longitudinal flows. These systems and their functions are explained in details in Chap. 13. Transverse systems have been shifted to only using longitudinal ventilation by mounting jet fans in the ceiling. This is considerably easier to build and much less expensive. The conceptual idea in unidirectional tunnels is to create a smoke free area upstream of the fire site. The main design parameters are the HRR in MW of a design fire and the critical velocity needed to prevent back-layering inside the tunnel. In Chaps. 4 and 5, different HRRs and fire growth rates are given and in Chap. 6, different design fire concepts are presented. One of the main risks with ventilation systems is the possible enhancing of the fire development and increased risk for fire spread between vehicles. Fire spread in tunnels is presented comprehensively in Chap. 11. Fire spread as governed by the flame length is presented in Chap. 9 and as governed by the heat flux in Chap. 10.

The evacuation systems consist of escape routes at equal intervals inside the tunnels or rescue stations. This is usually arranged as a bypass between two parallel tunnel tubes or safe havens built specifically for evacuees. These distances varies considerably and are usually determined through national laws, directives, standards or guidelines. It is also possible to perform an engineering analysis considering the effects of the fire on the tunnel users that need to evacuate the tunnel. This type of analysis requires a sound knowledge of fire physics and the dynamics of the smoke products, for example, smoke stratification as presented in Chap. 12, and heat development inside the tunnel. The more advanced methods can be combined with advance Computational Fluid Dynamic (CFD) calculations, as presented in Chap. 17.

Simpler one dimensional (1D) calculation can also be used for sensitivity analysis. The 1D models are presented in Chap. 7 (gas composition), Chap. 8 (gas temperatures) and Chap. 14 (visibility). Knowledge about gas composition is vital when performing this type of calculation. Further, the smoke densities and temperature distribution are important. The basic data about gas composition and production of smoke and gases in different types of fires are given in Chaps. 7, 8, 14 and 15 (tenability). By calculating the walking speed, which is dependent on the visibility, and the hazardous environment the evacuees are exposed to (toxic gases, temperatures), the evacuation time when (or not) they reach a safe region can be derived.

The detection systems are necessary to alert the tunnel users, fire services and the controller of the tunnel systems to an incident. Due to the variation in fire development and conditions in the tunnels, every fire is unique and can be difficult to discover. The main indicators from fires are convective heat, smoke particles, gas composition or radiation. Nowadays, digital analysis using surveillance cameras inside the tunnels are also used as a part of the alerting systems. Depending on the technology used and the fire scenarios, the response of the systems varies. The most common system is based on line detectors, where the convective heat from the fire indicates that there is a fire. Depending on the fire size, tunnel height and ventilation rate, the systems can vary in response time. Other systems detect the smoke particles travelling inside the tunnel which requires that the smoke is lifted by the convective flow (buoyancy) to the location of the detectors. Flame detectors are another type of system that observes the electromagnetic radiation from the flames. If the fires are hidden inside the vehicles, such detectors are not able to detect the fire. Systems based on gas composition are also available. The common factor with all these systems is the dependence on the physics of the fire which, therefore, requires a good basic knowledge on fire dynamics in tunnels when working with these systems. The detection technology is briefly described in Chap. 16, and the basics for the indicators for these systems are well covered through chapters such as 7, 8, 10, 12 and 14.

The suppression systems work actively to control or prevent further fire development in vehicles inside tunnels. The generic name for such systems today is fixed fire fighting systems (FFFS), which covers most type of water based systems. The dynamics of such systems are given by the interaction of water spray with the convective heat from the fire and the suppression of heat and combustion products at the fuel surfaces. The cooling mechanism and downward drag of smoke are parameters that require good basic understanding by engineers and researchers when designing such systems. The water spray systems create different sizes of droplets and thereby interact with the fire in different way. Large droplets penetrate more easily towards the fuel surface, while small droplets evaporate more easily in the convective gas volume and thereby reduce the gas temperature effectively. This in turn affects the re-radiation to the fuel surface and further development of heat and smoke. An understanding of the energy balance at the fuel surface is vital and gives an indication of the effectiveness of the system. The basic knowledge of fire physics and the interaction of the water with the fire are described in detail in Chap. 16. Large-scale fire tests with FFFS are presented in Chap. 16, while large-scale and model scale tests where no FFFS are involved are presented in Chap. 3.

The model scale technique is an important instrument in order to obtain useful and reliable information concerning fire dynamics in tunnels. In Chap. 18, different types of scaling techniques are presented and outlined. The model scale technique is one of the most effective methods in gaining new knowledge and therefore it is important to present the theories behind it. Much of the knowledge presented in this book actually comes from model scale experiments carried out by the authors for different types of conditions in tunnels. Another knowledge base to obtain valuable information is real incidents occurred in tunnels. In the following section, analysis of numerous large fire incidents is given.

1.4 Incidents in Tunnel

In order to better understand the physics of tunnel fires, a collection of previous large tunnel fires are analysed. These fires have occurred in road tunnels, rail tunnels or metro tunnels. The main difference between the various incidents lies in the way these incidents occur and develop initially.

1.4.1 Fires in Road Tunnels

The road tunnel incidents presented here are typically related to the type of occurrence, that is, a collision between vehicles, collision between a vehicle and tunnel structure or single vehicle fire in an engine compartments, brakes or due to other technical mishaps. The behaviour of the drivers, either controlling the vehicle or as an evacuee, is a major factor in the outcome of these incidents. Fighting these fires as long as only a single vehicle is burning, and there is access to a ventilation system, is usually not a problem. The problem arises when multiple vehicles become involved and there are many evacuees involved in the incident.

The first impression when studying road vehicle fires is that the presence of heavy goods vehicle (HGV) fires dominates the consequences, both concerning the damage to the tunnel construction and in terms of the number of fatalities. Hazardous goods (bulk) transports have seldom been found to be involved in large incidents. One possible reason for this is the safety education given to the drivers and the regular maintenance of the vehicles. The commodity transported by general HGVs has the same potential to cause havoc as hazardous goods transport with petrol or diesel in a tunnel fire. The fire tests in the Runehamar tunnel in 2003 [8] clearly exhibited this.

Although the largest contribution in tunnel fires is from HGV fires, the most frequent fires are single vehicle fires, such as passenger car fires. Buses and coaches are not frequently involved in tunnel fires, but there is definitely the potential for a large incident compared to a single HGV or passenger vehicle fire. The incitement to install extinguishing systems in this type of vehicles will reduce the risk in the future. The greatest problems arise when multiple vehicles become involved in the initial incident. The risk for fire spread becomes the largest threat.

The fire physics presented in this handbook will teach the reader that the tunnel ceiling height in combination with the ventilation conditions is the single most important parameter for further fire development once a fire has started. The initial type of fire load in the vehicles involved in the incident is also a contributing factor. The tunnel height is probably the most underestimated parameter in fire hazard in tunnels. The lower the tunnel height, the higher the risk for continuous fire spread, especially in queue situations or when large vehicles become involved. This is due to the long flame lengths and thereby the high incident heat fluxes created by these fires. The flame lengths, heat fluxes and risk for fire spread are presented in Chaps. 9, 10 and 11, respectively.

Table 1.1 contains a summary of large fire incidents involving HGV fires, where no direct fatalities have been documented. In Table 1.2, a summary of large fire incidents involving HGVs where fatalities are documented is presented. In many of these incidents, the passengers or drivers were killed in the accident itself, not necessarily because of the fire.

Lönnermark [12] made an analysis of fires involving HGVs and found that fires in tunnels involving only one burning HGV very seldom lead to fatalities, but as soon two or more HGVs are involved, the fire most often leads to fatalities. These conclusions are reflected in what can be interpreted from Tables 1.1 and 1.2.

Kim et al. [13] continued the analyses of different types of accidents and identified the basic parameters for why certain road tunnel fires developed to catastrophic fires while others did not. They concluded that all collision fires where HGVs were involved and the fire spread from the initial vehicles involved in the collision are extremely hazardous to road users and special measures should be taken to avoid them. Kim et al. also indicated that it is likely that the fire rescue service will be faced with a sudden increase of gas temperatures and come across a substantial number of evacuees which are injured, unconscious or even dead in such fires.

In Kim et al.'s study [13] it was found that the collision fires involving only passenger cars at the initial stage of the fires did not spread to the neighbouring vehicles. It was reported that the fires were easily extinguished by the driver or the fire brigade [14]. Although fire spread in fire accidents involving a single vehicle is not common, single fires can propagate to other vehicles when the initial fire originated from a HGV with a large fire load.

Table 1.1 Summary of fires in road tunnels involving HGVs, lorries or trucks, *not* leading to fatalities [9–11]

Year	Tunnel, length	Location	Cause of fire	Duration	Consequences for		
					People	Vehicles	Structure
1968	Moorfleet L = 243 m	Hamburg, Germany	Breaks jamming	1 h 30 min	None	1 HGV	Serious damage for 34 m
1976	B6 L = 430 m	Paris, France		1 h	12 slight injured (smoke)	1 HGV	Damage for 150 m
1983, 3 Feb.	Fréjus, L = 12,868 m	Modane, France–Italy	Gear box breaking	1 h 50 min	None	1 HGV	Serious damage, 200 m
1984	St. Gotthard, L = 16,322 m	Goe-schenen, Switzerland	Fire in engine	24 min	None	1 HGV	Serious damage for 150 m
1993	Fréjus L = 12,870 m	France/Italy	Engine fire	2 h	None	1 HGV	
1994, 5 July	St. Gotthard L = 16,322 m	Goe-schenen, Switzerland	Friction wheel	2 h	None	1 HGV (with trailer)	Serious damage to ceiling, pavement and equipment 50 m, tunnel closed for 2.5 days
1996, 18 Nov.	Channel tunnel L = 50,000 m	England–France	Suspected		30 injured by smoke	10 HGVs	Severe damage to the tunnel ceiling
1997, 31 Oct.	St. Gotthard L = 16,322 m	Switzerland	Fire in engine compartment	1 h 20 min	None	1 HGV	Serious damage 100 m
2000, 14 July	Seljestads-tunnel L = 1272 m	Norway	Engine compartment	45 min	6 injured	1 HGV 6 cars 1 MC	Severe damage
2002	Tauern L = 6400 m	Austria	Faulty engine			1 HGV	Severe damage
2004	Fréjus L = 12,870 m	France/Italy	Breaks caught fire	2.5 h	30 evacuated	1 HGV	
2006 20th Sep	Mastrafjord	Norway	Engine problems	0.5 h	None	1 HGV	

Table 1.1 (continued)

Year	Tunnel, length	Location	Cause of fire	Duration	Consequences for		
					People	Vehicles	Structure
2008 16th June	Södra Länken	Sweden	Engine problems	0.5 h	None	1 HGV	
2010 20th Jan.	Trojane L = 3000 m	Slovenia	Multiple collision involving 6 HGVs	<1 h	5 injured	2 HGV	Damage to tunnel linings
2011 29th Mar.	Oslofjord L = 7230 m	Norway	Engine problem	<1 h	4 injured	1 HGV	
2011 23rd June	Oslofjord L = 7230 m	Norway	Engine breakdown	<1 h	12 injured	1 HGV	Damage to tunnel linings
2013	Gudvanga	Norway	Engine problems	1 h	70 injured	1 HGV	Damage to tunnel linings

Table 1.2 Summary of fires in tunnels involving HGVs, lorries or trucks, leading to fatalities [9–11]

Year	Tunnel, length	Location	Cause of fire	Duration	Consequences for		
					People	Vehicles	Structure
1978, 11 August	Velsen L = 770 m	Velsen, Netherlands	Front–back collision	1 h 20 min	Five dead Five injured	2 HGVs Four cars	Serious damage 30 m
1979, 11 July	Nihonzaka L = 2 045 m	Shizuoka, Japan	Front–back collision	4 days	Seven dead Two injured	127 HGVs, 46 cars	Serious damage 1100 m
1980, 17 April	Kajiwara L = 740 m	Japan	Collision with side wall and over-turning	1 h 20 min	One dead	Two trucks	Damage 280 m
1982, 7 April	Caldecott L = 1083 m	Oakland, USA	Front–back collision	2 h 40 min	Seven dead Two injured	3 HGV, one bus, four cars	Serious damage, 580 m
1987, 18 February	Gumefens L = 340 m	Bern, Switzerland	Mass collision on slippery road	2 h	Two dead	2 HGV one van	Slight damage
1993	Serra a Ripoli L = 442 m	Bologna, Italy	Vehicle out of control and collision	2 h 30 min	Four dead Four injured	4 HGV 11 cars	Serious damage to lining
1996, 18 March	Isola delle Femmine L = 150 m	Sicilia, Italy	Bus crashed into back of tanker		Five dead 34 injured	One tanker, one bus, 18 cars	Damage to lining and lighting
1999, 24 March	Mont Blanc L = 11,600 m	France–Italy	Not known	53 h	39 dead	23 HGVs, one small truck, nine cars, 1 MC	Severe damage (900 m), the tunnel closed for 3 years
1999, 29 May	Tauern L = 6400 m	Austria	Leakage of paints and varnishes	15 h	12 dead	16 HGVs 24 cars	Closed for 3 months
2001, 6 August	Gleinalm L = 8320 m	Austria	Front collision lorry-car		Five dead Four injured	1 HGV one car	
2001, 24 October	St. Gotthard L = 16,322	Switzerland	Collision	2 days	11 dead	13 HGVs 10 cars	Severe damage, 230 m, closed for 2 months
2003, 14 Apr	Baregg	Switzerland	Front–rear collision		One dead One injured		

Table 1.2 (continued)

Year	Tunnel, length	Location	Cause of fire	Duration	Consequences for		
					People	Vehicles	Structure
2005, 4 June	Fréjus L = 12,900 m	France/Italy	Engine fire		Two dead, 21 injured	4 HGV	10 km of equipment to be repaired
2006, 25 October	Eidsvoll L = 1200 m	Norway	Head collision, a car and a HGV loaded with hydraulic oil	1–2 h	Car driver died in accident, Two injured	HGV, Car	Two concrete element damaged, lighting, asphalt damaged
2006, 16 September	Viamala L = 700 m	Switzerland	A bus and two cars in a crash		Nine died, Five injured	Bus, two cars, fire spread to additional two cars	Damage to lining
2007, 23rd March	Burnley L = 3400 m	Australia	Rear–front collision HGV and cars	1 h	Three dead Two injured	Multi-vehicle pileup involving three trucks and four cars	FFFS, no damage
2007, 10th September	San Martino L = 4800 m	Italy	HGV crashed into wall		Two dead 10 injured	1 HGV	
2007, 12 October	Newhall L = 167 m	USA	Two HGVs collided	6–8 h	Three dead 10 injured	30 HGV one car	Severe damage
2009, 10th May	Follo L = 900 m	Norway	HGV collided with entrance wall	1.5 h	One dead	1 HGV	Severe damage, 60 tunnel concrete element replaced, 500 m technical installations
2014, 1st March	Yanhou	China	Two tankers		31 dead	42 vehicles destroyed	

Kim et al. [13] were able to show that fires in road tunnels can be divided into two main categories. One category is fire incidents which involve only one vehicle without any involvement or influence from other vehicles at ignition. The list of road 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 road tunnel. These kinds of fires are expected to occur suddenly without any previous signs so they have the potential to develop into a catastrophic fire. The first category was 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.

Kim et al. [13] proposed that the two categories (single fire and collision fire) can be divided into subcategories depending on whether the fire has spread or not. The fire spread was defined as fires propagated to another vehicle which is not engaged in the initial fire. The definition proposed by Kim et al. [13] of each incident category were as follows:

- *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 was that it was found to be one of the key factors determining the consequences of the tunnel fires studied. The spread of fire increased the intensity and size of the fire and hampered the operations of the fire brigade. Fire spread also involves more vehicles and road tunnel users in an emerging incident so it can potentially claim many casualties and economic losses. If a fire does not spread to neighbouring vehicles, the size or the intensity of the fire will be limited.

Forty three fires of Incident Category 1 (*IC1)* were included in this group. Of these, 25 fires occurred in HGVs, three fires in passenger cars, 14 in buses or coaches and one in a mobile crane. Among 48 single fires, fire spread was found in only five cases. Interestingly, all *IC2* fires originated from HGVs. These were either a petrol truck or lorries carrying a great quantity of combustible goods, for example, tyres in the Frejus tunnel fire of 2005, 9 t of margarine and 12 t of flour in the Mont Blanc road 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 t of carbon disulphate in the Holland tunnel fire of 1945. It is reported that most of

Table 1.3 Analysis on the previous fires in road tunnels [13]

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

[a] Incidents where only smoke is produced without flame are included into single fires

these five fires had unique factors which may have exacerbated the progress of the fire, that is, oil leakage (Mont Blanc road 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 to the vehicles.

Seven fires in *IC3* are summarized in Table 1.3. 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 road tunnel. 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 occurred 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.

The situation for the fire fighters becomes difficult to master, and access to the fire site depends very much on the technical equipment provided. The ventilation system is one example of such system, see Chap. 13. FFFS is also a technical system that can improve the conditions for fire fighters, although the final extinction needs to be carried out manually by the firefighters. The longer the tunnels the more difficult the fires will be to fight, unless there is access through escape routes.

1.4.2 Fires in Rail Tunnels

In rail tunnels, the fires are often related to technical failure in the rolling stock, either in locomotive machinery, the restaurant area, electrical system, ventilation system or arson. These fires are often observed by the passengers or staff, and can be dealt with directly. If the fire starts on the outside, it can be due to failure in hydraulic systems (leakage, spray etc.) or overheating of brakes. Such fires are more difficult to discover, and usually not possible to combat until full stop. After full stop these fires can develop fairly rapidly. In some cases, the cause of the fire is due to derailment/collision, but these types of fires are difficult to prevent due to the complexity of the incidents. Freight trains deserve special attention here, as there are very few crew members, but the potential for a fire of long duration is higher. Fighting fires in rolling stock is very difficult and places enormous pressure on the rescue services. The sites of rail accident can also be difficult to reach.

The potential for a huge incident with many fatalities is much higher in rail and metro tunnels or stations compared to road tunnels, simply because of the large number of passengers. The frequency, however, of serious fires in rolling stock is much lower than for road vehicles. The stringent fire requirements on interior and exterior solid materials in modern rolling stock and the type of potential fire risks can explain this difference. In road vehicles there are minimal fire resistance requirements, which are reflected in the consequences of road vehicle fires.

As mentioned previously, however, the potential for many fatalities in rolling stock fires is high, although the risk for fire spread is relatively low provided the initial fire in a given section of the train (inside a wagon), does not develop to a fully flashed over fire (fully developed). The fire development inside a carriage has the same governing physical parameters as a compartment fire. The fuel load, the ventilation conditions through openings such as doors or windows, and the size of the ignition source, are all important parameters for the fire development. The quality of the interior material and the windows are also very important. It is first after the fire becomes flashed over that there is a risk for continuous fire spread to neighbouring carriages. Such fires have occurred with disastrous outcome. In Tables 1.4 and 1.5, the Deagu fire 2003, the Kaprun fire 2001 and the Baku fire 1995 are all example of such fires.

Other types of rolling stock, such as freight trains, may also create hazardous situations, although they usually do not include numerous passengers. The potential for a significant and long duration fire is higher. Examples of such fires can be found in Table 1.4, for example, Summit 1984, Baltimore 2001 and Eurotunnel 1996 and 2008.

For freight trains carrying fuel tanks or HGVs, the main consequence is the damage to the tunnel structure, similar to that in case of a road tunnel fire. In passenger train fires, the main consequence is generally not the damage to the tunnel structure but the number of potential fatalities. Most fire incidents with passenger trains do

Table 1.4 A list of key fire incidents in rail tunnels [9, 14–17]

Year	Name Country Length	Initial fire location	Most possible cause or location of fire	Consequence
2008	Channel tunnel UK/France L = 51 km	Near the front of the train	One HGV	650 m damage
2000	Kitzsteinhorn Austria L = 3.3 km	Rear end of the train	Hydraulic oil leakage to electrical heater	155 dead
1999	Salerno Italy L = 9 km		Smoke bomb	Four dead Nine injured
1998	Guizhou Chaoyangba #2 China L = 0.8 km		Gas canister leakage, explosion	Six dead 20 injured
1996	Channel tunnel UK/France L = 51 km		Suspected arson	34 injured Severe damage to structure
1991	Dayaoshan tunnel China L = 14.3 km		Cigarette	12 dead 20+ injured
1984	Summit tunnel UK L = 2.6 km		Derailment 13 fuel tanks	Shut for several months
1976	Baocheng China		Derailment, fuel tanks	75 dead 38 injured
1972	Hokoriku Japan		Restaurant fire	30 dead 690 injured
1971	Wranduk Yugoslavia L = 1.5 km		Engine fire	34 dead 120 injured
1921	Batignolles France L = 1 km		Collision	28 dead

not correspond to a large number of deaths. This could be due to the fact that railway tunnels are high and of large cross-sections where people could have some time to evacuate through the portals or cross-passages before the toxic smoke completely descends to inhalation level. The channel tunnel having a small cross-section but equipped with a service tunnel and many cross-passages is an exception. For tunnels not equipped with cross-passages and other active fire protection systems, the consequences can be expected to be more serious.

Another issue for railway tunnels is that the longitudinal ventilation initially developed and commonly used for smoke control in road tunnels has been widely adopted in railway tunnels. In particular during the evacuation stage of a fire incident, this ventilation scheme could make the situation worse in some cases.

Table 1.5 A list of key fire incidents in metro tunnels [9, 14–17]

Year	Name Country	Initial fire source	Most possible cause or location of fire	Consequence
2003	Jungangno metro	In train	Arson, Petrol	198 dead and 146 injured
	Daegu, South Korea			
1995	Baku metro	Rear of 4th car out of 5	Electrical fault	289 dead and 265 injured
	Azerbaijan			
1991	Moscow metro	Underneath of a carriage	Electrical fault	Seven dead and over 10 injured
	Russia			
1990	New York metro US	Inside the tunnel	Cable	Two dead and 200 injured
1987	King Cross station	Escalator in the Station	Cigarette	31 dead
	UK			
1979	San Francisco metro	Underneath of a carriage	Electrical fault	One dead and 58 injured
	US			
1972	Hokoriku tunnel	Carriage	Restaurant	30 dead and 690 injured
	Japan			
1903	Couronnes metro		Electrical fault	84 dead
	France			

1.4.3 Fires in Metro Tunnels

A summary of the key incidents in metro tunnels is presented in Table 1.5. It can be seen that in these fire incidents, electrical fault is the main cause. Further, compared to railway incidents, the consequence of these metro fire incidents is characterised by more deaths. Arson fires require special attention. Despite the small number of arson fires, the resulting consequence can be expected to be most serious. The reason for the catastrophic consequences in these metro tunnel fire incidents is mainly due to the small cross-section of the tunnel and the large number of passengers on board and in the station. Nowadays, metro systems are becoming more and more complicated and constructed at numerous levels down to significant depths. Accordingly, fire safety issues will require greater attention in the future.

1.5 Summary

Catastrophic fires that have occurred in different types of tunnels continue to remind engineers and authorities that this is an important safety field. The large infrastructure projects being undertaken requiring significant investments, demand concomitant safety solutions that are sound and reliable. Without proper knowledge about fire incidents and experiences learned from them, we will not be able to continue developing such solutions. Therefore, it is very important to analyse incidents that have occurred and try to systematize them in order to understand what the key parameters are for the outcome of these incidents. The analysis carried out by Kim et al. on road tunnel fires is a good example of such analysis and systematisation. By dividing the incidents in road tunnels into four incident categories they were able to identify the critical issues, for example, the fire spread to adjacent vehicles. As long as the fire stays in one vehicle, it remains manageable albeit difficult to deal with. In order to better understand these incidents, we need to analyse them from the point of view of fire dynamics and the interaction of the tunnel, vehicle, mitigation and humans. The following chapters give a deep insight into the fire physics of tunnels and thereby constitute a very good knowledge base for future tunnel engineers.

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