4. TUNNEL FIRES

4.1. BACKGROUND

Tunnel fires have long been a key focus in discussion of tunnel safety. In *chapter 4* a short characterisation of tunnel fires is presented, followed by a discussion of relevant influencing factors and a list of data that should be collected on tunnel fires. The main part of *chapter 4* is concerned with data on tunnel fires, in particular fire rates.

International data and statistics on tunnel fires have been collected and published by PIARC in 1999, (PIARC doc. 05.05.B – Fire and Smoke Control in Road Tunnels) [7]. The report has been a key reference document for estimating basic fire rates in tunnels and is now more than 15 years old. In the report data are given for selected tunnels in selected countries.

Since 1999, the range and quality of data on tunnel fires has increased. For 12 countries, comprehensive information on tunnel fires could be collected and evaluated during the development of this report. The aim is to present statistical data on fire incidents in tunnels from different countries and other information which may be useful to describe the characteristics of real tunnel fires so that parameters of fire risk can better be estimated and handled adequately for instance in risk analyses, in the tunnel design phase as well as in the tunnel operation phase. Feedback from experience with fires can also serve as basis for evaluation of tunnel operation, action of emergency services as well as user behaviour

In the following focus is given to updating fire rates rather than discussing the consequences of fires, because the consequences of a specific tunnel fire are very much dependent on the specific circumstances of an individual event. As tunnel fires are rare events, an entirely statistical approach to the assessment of consequences of tunnel fires is not likely to be sufficient.

4.2. CHARACTERISTICS OF TUNNEL FIRES

The discussion on tunnel fires is often dominated by the extreme events which occurred in the Mont Blanc tunnel, the Tauern tunnel and the Gotthard Tunnel. However, in reality the majority of tunnel fires are relatively small events in comparison, which nevertheless may have the potential to develop into more serious events, depending on various influencing parameters. The confined space of a tunnel provides an environment in which untenable conditions may develop rapidly in case of a fire. Series of real fire tests have been performed in the context of various national and international research programs in order to confirm assumptions on fire sizes and fire behaviour; in these tests the focus again was on large scale fires with high heat release rates. These trials are performed under certain conditions and the results need to be verified by data on real fires in terms of fire statistics.

The collection of data for these statistical purposes requires a more stringent definition of events which should be considered as fires. Today there is different practise in different countries on what event is recorded as a fire and what is not (for the definition of the term "*fire*" in the context of this report see *chapter 1.2*). There is also different practice on how fires are detected and if the cause of the fire is recorded or not. The fire size is often not estimated nor recorded, so the fire size in many cases has to be estimated based on indicators. The different practises in the data collection can be explained by different factors, such as different tunnel locations (urban or rural), traffic density, varying level of monitoring due to tunnel length, etc. For a further improved understanding the frequency and severity of tunnel fires, it may be necessary to analyse fire occurrences, fire load, heat release rate, fire duration and development and possibly also fire causes and their consequences.

Some relevant key factors for the characterisation of tunnel fires are the following:

Development of fire
- Development speed:
  - slow development with smoke
  - rapid development
  - explosive development

Fire size
- fire load
- fully developed fire
- not fully developed fire
-

Fire causes:
- Collision
- Vehicle defect triggering a fire e.g. engine fire / overheated breaks etc.

The speed of fire development and the fire size are of significant importance with regard to tunnel safety. Both are influenced by the nature of the fire load, the technical conditions of the vehicles involved, the airflow conditions in the tunnel during fire development as well as the fire safety engineering design of the specific tunnel.

The maximum heat release rate of a fire depends on the quantity and type of material of the fire load as well as the boundary conditions of oxygen supply, tunnel characteristics and system response etc. Fires in personal vehicles rarely develop to high heat release rates, whereas fully developed fires in the cargo of heavy goods vehicles and pool fires potentially can develop into very high heat release rates.

The two types of tunnel fires (triggered by a collision or a vehicle defect) can be distinguished with regards to their characteristics: fires resulting from vehicle defect typically start in engine, exhaust system, wheels or brakes; seldom in the load. These fires in most cases are shielded fires which are likely to develop slowly in the first phase, with progressive development in later phase resulting in a fully developed fire. This type of fire development increases the opportunity to extinguish a fire (or delay its further development) either by the use of manual fire extinguishers, fixed fire-fighting systems and/or by responding fire fighters, before it is able to threaten the health and safety of people in the tunnel. Fires after collisions are often accelerated by (limited amounts) of fuel that has leaked as a result of the collision, hence the development is typically faster. Flammable liquid fires, i.e. pool fires with large amounts of flammable liquids, are extremely rare occurrences, which require a large amount of flammable liquid to be released (as a consequence of a collision or by other reasons).

4.3. INFLUENCING FACTORS FOR TUNNEL FIRES

A number of factors influence the fire occurrence rate, some of which are estimated based on expert judgement and indicators; and some of which may be estimated based on data and statistics.

It is normal to distinguish fires which are a result of collisions and fires which are considered as resulting from vehicle defect (e.g. a result of technical, electrical or mechanical defaults). The majority of vehicle fires occur as a result of vehicle defects. However, fires caused by collisions can have severe consequences as they may develop more rapidly and often involve persons who are unable to escape from the burning vehicle. In the following, the factors influencing collisions (and only indirectly influencing fires) are not discussed, because these aspects are already addressed in *chapter 3*.

In determining the likelihood or frequency of fire the following influencing factors are relevant:

- Collision rates
- Percentage of HGV traffic (because there may be a difference in the fire rates of HGVs and passenger cars)
- Gradients in the tunnel and the length of the gradient.
- Gradients on the routes leading towards the tunnel
- Combination of tunnel length and gradient
- Traffic composition / age and technical standard of the vehicles, as well as maintenance of heavy vehicles

The development and consequences of a fire, following ignition, is not discussed further in this chapter. Reference is made to the annex, where a representative sample of characteristic tunnel fires is reported.

In order to establish a better basis for quantifying the factors influencing fire rates, it is necessary to note all the relevant parameters in the recoding of a fire event. In the evaluation of this data it might be possible to establish the correlation between the indicating factor and the fire rate.

Up to now, statistics have been insufficient for the establishment of reliable models for the influence of gradients and combination of gradients and lengths on fire rates. For this reason the existing models may be regarded as expert judgements, which later may be supported by real data.

It can also be observed that the traffic composition in terms of the age and technical standard of the vehicles has an influence on the fire rate. In particular, it is of importance that the brakes for heavy vehicles are adapted to tunnels / mountainous routes with steep downwards gradients, and that the engine exhaust system and transmission can withstand the challenges of the upwards gradients. However, until now no statistical basis has been available for quantifying this influence.

It should be noted that statistical data are useful in order to establish models. In many cases, however, the statistical data must be combined with some sort of expert judgement. An entirely statistical model may for instance show that tunnels with monitoring seem to have a higher fire rates than tunnels without monitoring. Of course, this does not imply that the fire rate is influenced by the monitoring, rather that the monitoring system influences the quality of the data set.

4.4. DATA COLLECTION ON TUNNEL FIRES

To improve safety in tunnels there is a need to learn from the experience of real events. Tunnel fires occur relatively rarely, and therefore it is particularly important that all relevant aspects from these fires are reported. Independent of the fire characteristics (in particular fire size) it is crucial to document the relevant parameters to make them available for further evaluations, because even the experience of small incidents may be valuable in terms of improving safety. In this respect it is recommended to also document such incidents (e.g. smoke release without significant combustion) which are not defined as fires according to the definition of this report (see *chapter 1.2*).

As fires are rare events, a more detailed collection of information than for more frequent incidents is justified. In the future, the data collection itself could be further improved so that statistics on fires become more reliable. The following data from fire incidents should be reported:

- Tunnel data, name, unidirectional or bidirectional, length and gradient.
- Time of occurrence of the fire, (year, month, date and time in the day).
- Characteristic traffic data (AADT, traffic composition, in particular share of HGVs), specific traffic characteristics (in particular congestion) traffic situation before and during the event.
- Location of the fire in the tunnel.
- Fire characteristics:
  - Development of the fire (estimated time from the start to complete vehicle burning / extinguishing of fire).
  - Estimation of maximum heat release rate (MW).
  - Indication of temperatures during the fire.
  - Duration of the fire.
- Consequences of the fire:
  - Vehicles involved, (heavy vehicles and personal cars - number).
  - People involved (number).
  - Casualties (numbers, fatalities, injured, hospitalized, etc.).
  - Indication of damage to the vehicles involved (useful for estimation of fire size).
  - Tunnel damage (construction, technical equipment, etc. – also useful for estimation of fire size).
- Duration of the closure of the tunnel.
- Where and by which means the fire was detected.
- Cause of the fire, e.g.:
  - Collision.
  - Vehicle defects, mechanical, electrical (e.g. hot brakes).
  - Fire in technical installations in the tunnel.
- How the fire was extinguished.
- Fire department and other emergency services efforts during the rescue (which organisation, alarm time, time until arrival at fire site, time of commencement of firefighting, time taken to control the fire, time taken to fully extinguish the fire).
- Fire ventilation: type (longitudinal ventilation, smoke extraction etc.), effect (smoke propagation along tunnel related to time, back-layering.

- Performance of the technical tunnel systems; did all the systems perform as expected, or did they fail or show unexpected behaviour?
- Evacuation details:
  – Emergency exits, spacing.
  – Time of alarm/alert/announcement.
  – Time taken from fire alert to start self-evacuation.
  – Time to complete self-evacuation.
  – Number of persons evacuated.
  – Emergency services activities to support rescue.
  – Number of persons with physical difficulties that needed assistance.
  – How evacuated persons were provided with welfare or shelter.
- General observations with respect to behaviour of people involved in the incident should also be recorded

Furthermore all data recorded automatically by the various technical systems (e.g. video supervision, detection and alarm systems etc.) should be evaluated systematically.

4.5. AVAILABLE DATA

Since its publication in 1999 PIARC report 05.05B "*Fires and Smoke Control in Road Tunnels*" [7] has been one of the key sources for data related to road tunnel fires.

This report includes the following information:

- *Fire rates from individual tunnels in different countries, with a range of 0 – 250 per billion (10^9) vehicles. For example: For the Elbe Tunnel a fire rate of 90 fires per billion vehicle km is mentioned, with a distribution of 60 fires per billion vehicle km for passenger vehicles and 250 fires per billion HGV-km.*
- *The statistics of fires in tunnels in France are summarised as 10 – 20 fires per billion (10^9) vehicle-km in passenger cars and 80 per billion vehicle-km in heavy vehicles without dangerous goods (resulting in 20 – 30 fires per billion vehicle-km in traffic with 15% HGV-share). For the fires in tunnels in France an estimate of the rate of fires of different severity is indicated.*

In principle it should be noted that it is not possible to establish the basis for understanding the occurrence and development of fires on statistics only. The fire incidents described in *chapter 6* (together with all other known cases like the famous extreme tunnel fire events of Mont Blanc, Tauern, Gotthard, Via Mala Burnley etc. can be used to establish a qualitative knowledge of the possible course of events during a fire. "*Expert opinion*" shall in any case be based upon the knowledge about the available information on real fire incidents. Furthermore, with a detailed and comprehensive set of data describing the fires, key numbers and influencing factors can be established. In this section, statistical data is used in order to establish fire rates. Data and relevant information which were taken as a basis for the calculations of fire rates are reported in *appendix 4*.

The fire rates are presented in terms of rates per vehicle-km, which has made it necessary to collect also the traffic volume in tunnels for the relevant period and the geographical area covered by the data collection.

It should be noted that for some countries complete / comprehensive data were available (see right part of *table 6*) whereas for other countries only limited data could be gathered. For the following countries data could be gathered for the calculation of average fire rates (see *table 6*):

- Norway
- Netherlands
- Austria
- Germany
- Italy
- Spain
- France
- United Kingdom
- Czech Republic
- Japan
- South Korea
- Vietnam

TABLE 6 AVERAGE FIRE RATES FOR ROAD TUNNELS IN VARIOUS COUNTRIES

Country	Fire rate all vehicles (per 10^9 veh. Km)
Norway	15.0
Netherlands	3.2
Austria	6.5
Germany°	25.7
Italy	5.6
Spain	3.5
France	10.6
United Kingdom#	Insufficient data (10 – 20)
Czech Republic	17 - 25
Japan^	(38)
South Korea	6.4
Vietnam*	560

Notes : # Value from the UKs in parenthesis is a rough estimate.
^ The tunnels cover four tunnels with fire events only – the rate is an upper value for Japan.
* The statistics only cover one single tunnel.
° The available data covers only the 28 German TERN tunnels – also small fires are included
Background data concerning fire rates see *appendix 4.1*

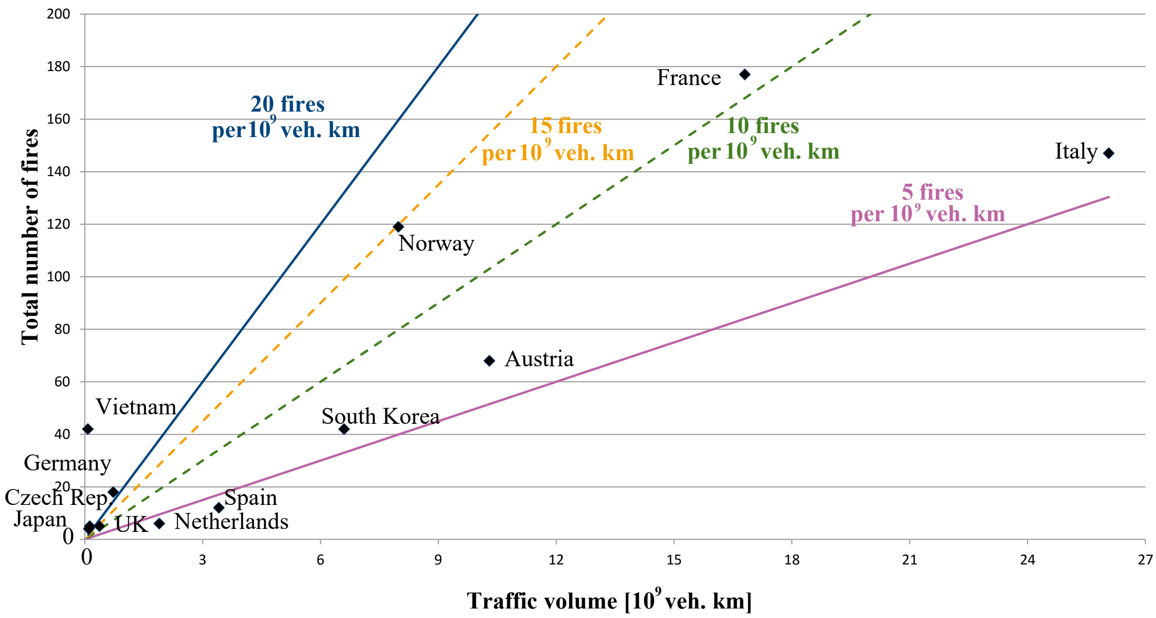

Illustration 8: total number of fires in the records shown in relation to the corresponding traffic for various countries - reference lines for fire rates

In *illustration 8* the fire rates are compared with respect to numerical fire rate per billion (10^9) veh-km. Instead of presenting the fire rates graphically, the total number of fires in the recording is shown in relation to the corresponding tunnel-traffic volume for each of the countries presented in *illustration 8*. Hence, in *illustration 8*, the slope of a line from (0,0) to the data point will correspond to the fire rate. The data points based on a high tunnel-traffic volume (here: Austria, France, Italy, Norway and South Korea) give more weight to the general fire rate than those with a low traffic volume. For more explanation of the basis for the rates of the individual countries, reference is made to the appendix.

As illustrated in *illustration 8*, the fire rates are generally within the interval 5 – 15 fires per billion vehicle-km. The tendency is that the rates are lower than the fire rates reported in PIARC 05.05.B from 1999 which as mentioned above were in the range of 0 - 250 per billion vehicle-km based on the individual tunnels with a weighted average of 45 per billion vehicle-km.

With the present-day level of detail for registration of fire events, it does not seem to be possible to establish a general rate of fires for HGVs, because the results are not consistent in the different countries. In Austria the fire rates of HGVs is 4 times higher than for all vehicles, in Norway Region East the fire rate of HGVs is 2 times higher than for all vehicles, whereas for Region West the fire rate of HGVs is not increased compared to all vehicles. For the Netherlands the rate is given for HGV fires over 25 MW, which cannot be compared to the other rates. For France the fire rate for HGVs is 70 % higher for unidirectional tunnels and 4 times higher for bi-directional tunnels, giving an average of 2.7 for all tunnels. In other countries the data are scarce or not given. The fire rate of HGVs is in PIARC report 05.05.B from 1999 specified as 4 times higher than the fire rate for all vehicles seems to be at the high end of the range based on the recordings from Norway, France and Austria.

Where possible the events which are "*smoke without significant combustion*" (see definitions in *chapter 1.2*) have been excluded from the statistical basis. Nevertheless these events may in some cases have been counted as fires, with the tendency that the fire rates presented above are upper values.

In general there is a significant uncertainty associated with the recording of the fires and the resulting fire rates. As explained in section 4.7 some fires may not have been registered ('dark' numbers), this phenomenon causes the estimated fire rates to be a lower bound value. Other differences in fire rates may be results of differences in tunnel design, driving culture, vehicles etc. in the different countries/tunnels.

4.6. TYPE AND SEVERITY OF FIRE EVENTS

In addition to the estimate of fire frequency rates for all vehicles and for HGVs, it is of interest to estimate the type and severity of fires. Estimates, registrations and expert judgements in this respect are reported in the *appendix 4.1*, particularly from Austria, South Korea, and to some extent from Norway and the Netherlands.

The causes of fires in Austria were recorded, and it was shown that a large majority of the fires (60 of 68) were caused by vehicle defects. 6 fires were a result of collisions (5 with passenger vehicles, 1 with an HGV) and for 2 fires the cause was unknown. This means that 90% of all fires were caused by self-ignition and 10% were caused by collisions.

The self-ignition was measured in relation to breakdowns. Whereas passenger cars have 1.5 self-ignitions per 1000 breakdowns, HGVs have 9.9 self-ignitions per 1000 break-downs. The rate of self-ignition for HGVs is influenced by the gradients of the route leading towards the tunnel. The rate of fires caused by self-ignition is thereby 3 – 6 times higher for HGVs than for passenger vehicles (based on the Austrian and French data). The data from Norway revealed only 1.5 – 2 times higher fire rates for HGVs compared to passenger cars.

As examples of the distributions, the recordings from Austria, South Korea and Italy are shown in *table 7, table 8, table 9*.

TABLE 7: DISTRIBUTION OF FIRE SEVERITIES FROM THE AUSTRIAN STATISTICS

Fire severity	nonHGV	HGV
Outside*	6 %	25 %
0-1 MW	58 %	37 %
5MW	36 %	23 %
30MW		14 %
100MW		1 %
	100 %	100%

** In the Austrian statistics tunnel fires are registered even though the vehicle on fire has come to standstill outside the tunnel just before entering or just after exiting.*

TABLE 8: DISTRIBUTION OF FIRE SEVERITIES BASED ON DATA COLLECTED FROM THE TUNNELS ON THE SOUTH KOREAN EXPRESSWAYS

Fire severity	nonHGV	HGV
1 MW	77%	17%
5MW	23%	42%
25MW		33%
50 MW		8%
100MW		
200MW		
	100%	100%

TABLE 9: DISTRIBUTION OF FIRE SEVERITIES ACCORDING TO ITALIAN ANAS GUIDELINES [48]

Fire severity	nonHGV	HGV
0-1 MW	40%	85%
5 MW	59%	
8 MW	1%	
15 MW		12%
30 MW		2%
50MW		1%
	100%	100%

It should be mentioned that there is a much higher degree of uncertainty in the numbers describing fire size than in the fire rates, because the information on fire size often is scarce and imprecise in the fire data recordings.

It shall be pointed out, that this information is in particular relevant for risk assessment, because it influences the results for fire risk modelling significantly. The data reflects the situation which can be expected in a road tunnel, without specific measures influencing fire development (like early fire-fighting or active fire-fighting systems). A clear distinction has to be made to the design fire size, which is a deterministic value defined in prescriptive regulations, which serves as a basis for design requirements (e.g. the layout of a tunnel ventilation system).

4.7. DARK NUMBERS / MONITORING

It is a possibility that some tunnels have had fires even though the fires do not appear in the statistics. These missing data may be described as ‘dark numbers’.

The registered fire rate is strongly dependent on the monitoring, see *illustration 9* (taken from the Norwegian data, where tunnels with and without monitoring are distinguished). The difference between the fire rate in tunnels with and without monitoring can give an idea about the dark numbers. On the assumption that the event rate for all tunnels would be the same as in the tunnels with monitoring, the dark numbers appear to be more than twice the actual recorded numbers.

Furthermore, in the statistics the events which have occurred in the past are generally not as well represented as those which have occurred recently. It can be seen in the Norwegian data that the fire rate has an increasing tendency with time, which contradicts the general perception of reducing fire rates with time. The results indicate that the records in the past may be incomplete.

It should be noticed that the dark numbers may primarily be associated to the less serious fires. In a tunnel without monitoring a modest fire may occur (and be extinguished by use of fire extinguishers or similar) without being reported to the police and fire brigade. A serious or very serious fire where the fire brigade is necessary for extinguishing the fire or where severe damage occurs will likely be reported by the fire brigade and police. These fires are most likely included in the statistics.

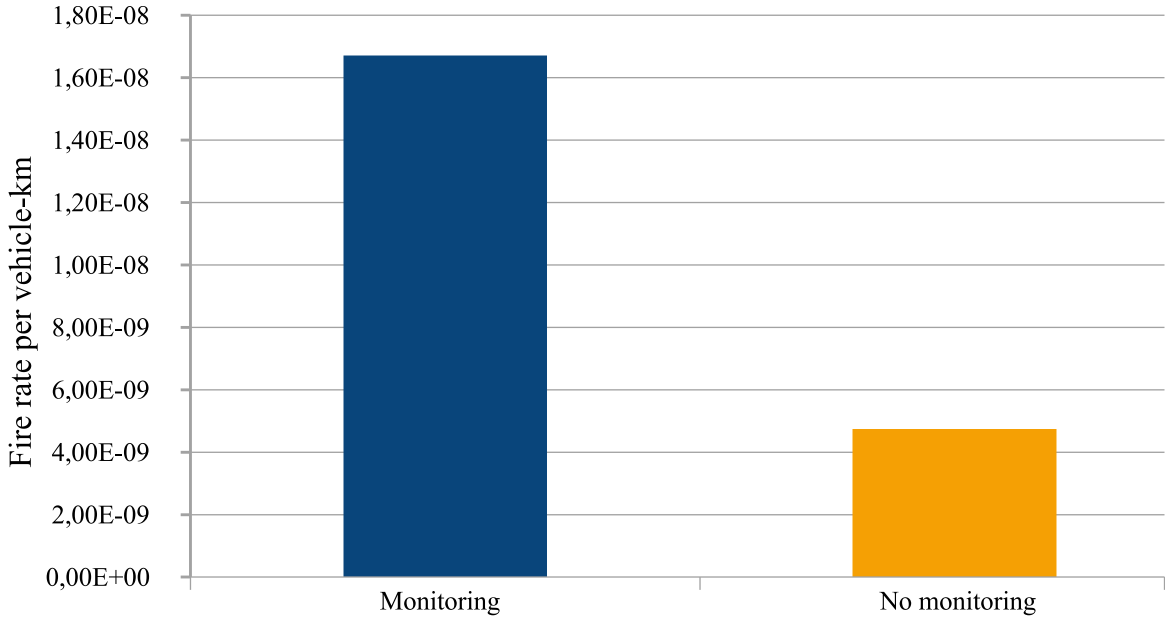

Illustration 9: comparison of fire rates in tunnels (in norway) with and without monitoring

As it appears from this result, a complete and comprehensive data collection is important.

4.8. APPLICATION OF THE DATA AND CONCLUSIONS

In various regulations, it is required that decisions are made based on risk assessment: this includes both the national tunnel guidelines and the European Directive 2004/54/EC. Furthermore, it has become good practice to carry out risk analyses for many tunnels in design as well as in operation and base decisions on safety systems / fire protection systems on these risk analyses (see *chapter 6*, which is discussing the experience in applying risk analyses). However, in order to estimate the expected fire frequency in a tunnel, it is necessary to have a basis of fire rates as well as information on fire size and fire development.

In the present chapter, fire rates have been estimated for tunnels around the world.

It seems that an "*average tunnel*" has a fire rate in the order of magnitude 5 – 15 fires per billion vehicle km. The scatter of the rates from tunnel to tunnel is very significant and a single tunnel investigated had a fire rate of over 500 fires per billion vehicle km. A number of factors may influence the recorded fire rates, for instance: tunnel design, location of the tunnel, geometry of the road, monitoring, technical standard of the vehicles, traffic regulation, speed limits, driving culture etc.

The data collection of fire events is serving as basis for the fire rates and for the risk analyses, which in turn may lead to the decision of safety measures in tunnels. Therefore, it is important that reliable data are collected in future for a large number of tunnels, so that the statistical basis can be improved in the coming years.

When the fire frequency of a given tunnel is estimated it is also necessary to evaluate which basic fire rate will be applicable and take into account the influence of the special characteristics of this tunnel on the fire rate (in particular its traffic characteristics and the technical standard of vehicles using this tunnel).

Fire rates should be used with care, and evaluation of the applicability and modification of the rates for an application for a given tunnel should be done by experts with experience in tunnel safety. When the above conditions are fulfilled, the fire rates can be applied in order to achieve safety systems for the tunnels which are balanced in relation to the fire risk.