SOLIT Safety of Life in Tunnels

Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems

Scientific Final Report of the SOLIT² Research Project prepared by the SOLIT² Research Consortium

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This document was produced with best knowledge and with great care. These documents and its annex documents are for the use of experienced fire protection experts. The reader has to evaluate the application of this document for each specific case separately.

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The scientific research project SOLIT² - Safety of Life in Tunnels was promoted by the German ministry of economics and technology (BMWi; Code No. 19S9008) based on a decision of the German Bundestag. All members of the consortium have set up separate scientific reports related to their aim of study. Most outstanding outcomes have been concluded in the present Guidance. The Guideline has been set up jointly among the consortia members and presents the common final report. The Guideline is part of the work package. All individual reports are available on behalf of the project coordinator.

Imprint:

Engineering Guidance for a comprehensive evaluation of tunnels with fixed fire fighting systems

The following annexes pertaining to this guidance are also available:
Annex 1: Status analysis
Annex 2: Selected Results from Full Scale Fire Tests
Annex 3: Engineering Guidance for Fixed Fire Fighting Systems in Tunnels
Annex 4: Application Example for a Risk Analysis
Annex 5: Safety Evaluation of Technical Equipment
Annex 6: Life Cycle Costs of Technical Equipment
Annex 7: Fire Tests and Fire Scenarios for Evaluation of FFFS

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Annex 2: Selected Results from Full Scale Fire Tests
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Annex 5: Safety evaluation of Operating Technology
Annex 6: Lifecycle Costs of Operating Technology
Annex 7: Fire tests and fire scenarios for Evaluation of FFFS

Part 1 Preliminary Remarks

1.1 Introduction

This guidance is designed to provide a methodology to engineers and other people familiar with fire protection in road tunnels to fully examine, evaluate and plan the component parts of a tunnel safety system. The focus is on the use of fixed fire fighting systems (FFFS) and the interaction of these systems with other safety measures. Starting with the basic technical principles, the aim is to show how to evaluate and plan the possible installation of an FFFS.

The starting point is the safety level stipulated by region-specific laws and approved technical regulations. One example of this is the German directive governing the equipment and operation of road tunnels ("Richtlinie zur Ausstattung und zum Betrieb von Straßentunneln", or RABT); the focus is based on fundamental methods and processes. This ensures that the principles can be transferred to other countries and to their corresponding prescriptions.

The function of this guideance consists of showing how technically elaborate and often cost-intensive measures can be replaced or compensated for by other, more efficient measures - and in particular through the installation of an FFFS. ("Trade-off"). The aim is use a reasonable combination of individual measures, depending on the actual design of the structure concerned, to improve the safety of people, the safety of the structure or the tunnel availability at a similar cost or to achieve the same level of safety at a lower cost.

Along with showing the effectiveness and the evaluation of individual protection measures, the guidance also describes processes for a complete evaluation and the minimum requirements needed to achieve this.

1.2 General set-up

This guidance document was produced by the SOLIT² research project, which was sponsored by the German Federal Ministry of Research and Technology following a ruling by the German Federal Parliament. The guidance describes the methods and minimum requirements for engineers and specialist designers familiar with the material that will enable them to carry out a comprehensive design process for a tunnel safety system and to assess its effectiveness and economic benefits.

Further configurations, background information and examples of application of the method can be found in the corresponding documents in the annexes to this guidance. In this document published considerations reflect the subject related perceptions of the consortium members. The measurements results used here are exemplary and refer to FFFS that were used during this research project as well as FFFS that have been tested during the previous research projects SOLIT, SAFE[1] and UPTUN. In the Engineering Guidance described outcomes refer to publically available test data, sources as well as personal experiences and considerations made by individual members of the research consortium.

The outcomes of the research consortium cannot be in any case directly transferred to other types of systems. The Guideline addresses primarily high pressure water mist and deluge water spray systems and – as far as information and knowledge was available – also FFFS based on foam. Statements concerning compressed air foam FFFS have not been made due to lack of information among the consortium members. If statements are made concerning foam based FFFS it addresses to foam based FFFS without involving compressed air.

The measurement results are only shown to illustrate the methodology used in this Guideline.

1.3 Explanation of terms

AFFF	Aqueous film forming foam
CFD	Computual Fluid Dynamics
Design fire curve	Size of used fire for the dimensioning of fire protection installations. Not related to the maximum fire size.
FFFS	Fixed Fire fighting system
HRR	Heat Release Rate of fires
MADM	Minimum Absolute Derivations Method
NFPA	National Fire Protection Association
RABT	Directive governing the equipment and operation of road tunnels
RAMS	Reliability, Availability Maintainability und Safety

[1] Project by EUROTUNNEL S.A.

Specific safety level	The safety level which is achieved by fulfilling certain protection goals.
Safety	Including safety of tunnel users, emergency services and infrastructure.
VDS	VdS Schadenverhütung GmbH
ZTV-ING	Additional technical contract terms and conditions and guidelines for engineering works

1.4 Additional standards and regulations

- NFPA 502: “Standard for Road Tunnels, Bridges, and Other Limited Access Highways”, Current version: 2011
- NFPA 750: “Standard on Water Mist Fire Protection Systems”, current version: 2010
- NFPA 20: “Standard for the Installation of Stationary Pumps for Fire Protection”, Current version: 2010
- NFPA 13, Installation of Sprinkler Systems; Issue 2010
- RABT: "Directive governing the equipment and operation of road tunnels", Current version: 2006 (Richtlinien für die Ausstattung und den Betrieb von Straßentunneln)
- PIARC – FFFS: "Road tunnels: an assessment of fixed firefighting systems", Current version: 2008
- UPTUN "Guideline for Water Based Fire Fighting Systems for the Protection of Tunnels and Sub Surface Facilities" WP251
- ZTV–ING: "Additional technical contract terms and conditions and guidelines for engineering works", Current version: 2010 (Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten)
- 2004/54/EG: European Parliament directive governing minimum safety requirements for tunnels in the Trans-European road network, Current version 2004
- Evaluation of the safety of road tunnels, Issue B66. BASt
- Manual for the safety evaluation of road tunnels according to RABT 2006 (Section 0.5), BASt
- EN 54-4, Fire detection and fire alarm systems
- EN 12259-1, Components for deluge and water spray systems
- EN 12845, Automatic sprinkler systems – Design, installation and maintenance.
- EN ISO 14847, Rotary positive displacement pumps – Technical requirements (ISO 14847:1999).
- VdS 2108: Richtlinien für Schaumlöschanlagen: Planung und Einbau, Edition 2005-05
- VdS 2109: Sprühwasser Löschanlagen, Planung und Einbau, Edition 2012-06
- European Arrangement concerning the international carriage of dangerous goods by road (ADR)
- Bundesfernstraßengesetz in der Fassung der Bekanntmachung vom 28.Juni 2007 (BGBI. I S. 1206), das zuletzt durch Artikel 6 des Gesetzes vom 31. Juli 2009 (BGBI. I S. 2585) geändert worden ist.

1.5 Sources

The reference sources used in this scientific repot can be requested from the project coordinator at contact@solit.info as far as they are available to public and not confidential.

Part 2 Basic principles

2.1 Area of application

This Guidance is designed primarily for the evaluation of safety systems in road tunnels or similar structures. The evaluation is based on a risk-based approach. The length and configuration of the tunnel are immaterial; it is the risks that exist in each individual situation that must be taken into consideration. The risk factor of the individual structure is determined by the frequency of possible damaging events, e.g. the incidence of fire with low or high traffic density of trucks, as well as the effects of the damage.

The methods and minimum requirements of this guidance may also be applied to other types of structure with a similar risk and danger potential or profile. In the case of each method shown here it is necessary to check to see if it is applicable according to the specific size, geometry, usage and design of the tunnel or other structure in question. This is particularly important in the choice of input data for calculation and simulation models.

The starting point for the choice of protection targets and the consequent starting parameters for the calculation and evaluation of compensation options is the responsibility of the planner or the body responsible for issuing the approval. However, the protection targets should be defined in accordance with the accepted technical regulations and in line with European Directive 2004/54/EG (Minimum safety requirements for tunnels in the Trans-European road network).

The general methods contained in this guidance can then be applied to individual protection targets that differ from these e.g. targets based on other regulations. This must be documented in the appropriate manner for verification purposes.

2.2 Protection targets and current technology

The infrastructure of tunnels as well as risk prevention measures is frequently subject to different regulations in different countries. However, the protection targets generally do not differ from each other and can be summarized as follows [LAK 2012]:

- Personal safety,
- Structural safety,
- Support/Facilitate emergency rescue
- Fire fighting.

In each country, the minimum requirements and measures needed to achieve these protection targets are described in different directives or regulations.

In Germany, personal and structural safety is the responsibility of the contracting authority[2] of the structure in question (e.g. federal government, federal state and local authority) and is usually covered by ZTV-ING and RABT.

In Germany, danger prevention[3] is the responsibility of the individual state and is therefore regulated by the fire brigade and emergency services laws and regulations of the individual federal states.

This task sharing requires very close coordination and collaboration from the design stage of a tunnel safety system onwards, so that all measures can be sensibly combined and coordinated.

Since more and more tunnels are being operated by private firms e.g. financed by tolls within the framework of public-private partnerships (PPPs), and there is also an increasing awareness of the economic importance of the traffic infrastructure, the following specific objectives are becoming more important in practice, along with the aforementioned general protection targets, even if they have not been considered of any particular importance hitherto in the relevant standards:

- Reduction of structural damage
- Reduction of costs in the event of an incident
- Maintenance of high availability
- Reduction of costs to the economy

The protection targets and the measures currently applied are described in brief below.

2.2.1 Personal safety

Uses of tunnel systems must, in the event of an incident (fire) have the opportunity, over a certain period of time, to leave the tunnel safely by themselves or to reach safe areas (self-rescue). Due to the particular conditions present in a tunnel it cannot be assumed that emergency rescue services, such as the fire brigade, will be able to provide prompt assistance due to time delays (arrival, advance movement within tunnel).

In Germany the RABT concept assumes that reaching a safe area infers a successful self-rescue. Safe areas include emergency exits and

[2] In road building terms the contracting authority in the Federal Republic of Germany is the institution that is responsible for the planning, construction, operation and maintenance of a road designed to carry public traffic. This is usually a public body (state, local authority).

[3] This generally includes emergency response and fire fighting services as well as other danger prevention measures implemented by the fire brigade.

portals. Various measures are provided to help with self-rescue, such as the construction of emergency exits and escape tunnels, the provision of escape route markings and, in some cases, loudspeaker announcements or announcements over the radio in the event of an incident.

Longer tunnels are provided with fire ventilation systems in order to create a survivable atmosphere in the tunnel during the period required for self-rescue. When a longitudinal ventilation system is used in tunnels designed for one-way traffic the smoke is forced to travel in the direction of the traffic flow in order to keep smoke away from the area where traffic has come to a standstill and there are still people present.

When using transverse or semi-transverse ventilation systems in very long one-way traffic tunnels [4] or long two-way traffic tunnels or one-way traffic tunnels[5] with daily traffic jams, on the other hand, attempts must be made to extract the combustion gases in order to limit the localised spread of smoke and maintain a relatively smoke-free layer close to the ground. The appropriate layer of smoke depends on the size of the fire and therefore the amount of smoke, the size of the cross-section of the tunnel, and the longitudinal air flow under design conditions. First of all the existing longitudinal flow must be safely controlled so that a layer of smoke is able to form. This stratification can be disturbed by turbulence, due for example to vehicles in the tunnel.

When judging the effect of fire ventilation it is important to take into account that there can be some considerable time between the detection and localisation of the fire and the full effectiveness of the system. This can be particularly problematic in the case of rapidly developing fires (e.g. liquid fires) that produce a lot of smoke and where there are significant changes of gradient within the tunnel.

2.2.2 Structural (passive) protection

2.2.2.1 Basic principles

In Germany passive fire protection involved in tunnel construction is regulated by the ZTV-ING. Regulations and specifications required by other countries can be applied using the methods in the guidance.

Basically, ZTV-ING requires a tunnel to be so designed that “in case of fire

- no damage should arise that puts the stability of the tunnel at risk,
- no lasting deformation of the structure is caused which limits the usability of the tunnel and
- jeopardises the long-term leak tightness."

The ZTV-ING insists that construction measures must be taken to ensure that the load-bearing reinforcements are never heated to temperatures over 300 °C. In general this is achieved for the current ZTV-ING test fire curve through a concrete covering of 6 cm. The ZTV-ING defines typical design fires in the form of a design fire temperature curve.

However, as has already been mentioned, the protective effect of the concrete covering is significantly influenced by the duration and intensity of the fire as well as the composition of the concrete outer covering.

The specification of passive fire protection measures is made in accordance with local conditions, economic viability and project-specific protection targets. In general the construction measures provided by the ZTV-ING for passive fire protection are sufficient. Where this is not the case additional protective construction measures can be applied under certain circumstances.

2.2.2.2 Structural fire protection in tunnels

According to ZTV-ING, structural fire protection measures in tunnels primarily serve exclusively to maintain the stability of the structure and avoid indirect personal injury, through e.g. the spalling of concrete parts. So-called passive structural fire protection measures do not, however, reduce the direct effects of a fire on tunnel users, emergency services and vehicles in the tunnel.

Depending on the specific requirements in each case the following passive fire protection measures are usually applied today:

Normal concrete with no additional fire protection

The inner coating of the tunnel is only designed to cope with a normal fire in accordance with the ZTV-ING. This is acceptable when the temperature and duration of the fire are expected to be relatively low, when the probability of a fire is low and when the scale of the damage that could be expected [6] in the event of a fire is acceptable.

Normal concrete can be protected through a higher concrete outer coverage on the load-bearing rein-

[4] According to RABT 3,000 m or longer

[5] According to RABT 1,200 m or longer, or from 600 m or longer depending on the local situation

[6] So far we have only looked at the damage to the structure, rather than the economic damage caused by the tunnel being out of action.

forcements to guard against too much spalling and the subsequent loss of load-bearing capacity in the event of a fire. The additional ceiling reinforcement required by the ZTV-ING for public construction work to guard against spalling[7] is only required for suspended ceilings in the case of private construction work.

No special concrete formula is required, which means that renovation work can be carried out after a fire using normal concrete. However, this limits the protective effect in terms of the reinforcement and a larger excavation line is therefore required.

Special fire protection concrete

The addition of polypropylene fibres (PP fibres) to the concrete and the use of special aggregates (basalt) and the limitation of granularity has been proved in oven tests on concrete test samples to give a much lower spalling range and significantly smaller spalling surface than is present in normal concrete. This is due, among other things, to the fact that in the event of fire the polypropylene fibres melt on the side exposed to the fire and therefore reduce the steam pressure within the concrete by creating additional pores. Instead of bursting, the basalt aggregate becomes caked in the heat [HAA 2008].

These measures lead to a significant reduction in the spalling of the concrete and therefore reduce the overall damages in the event of fire without the need for a larger excavation line. At the same time, unlike e.g. with the use of fire protection panels, there is no obstacle to a regular visual inspection of the load-bearing structure.

Furthermore, after a fire the concrete would lose its fire protective effect and the damaged concrete would have to be replaced.

The actualization of the ZTV-ING, launched on 21.09.2012 (“Allgemeines Rundschreiben Straßenbau Nr. 13/2012) envisages the use of polypropylene fibre concrete (PP-fibre concrete) for an extended passive fire protection in road tunnels. When using PP-fibre concrete no galvanised mash reinforcement is required.

Fire protection claddings (fire protection panels or fire protection plaster)

In order to provide effective protection for the structural concrete in tunnels from the effects of fire it is also possible to install fire protection panels or fire protection plaster.

Both options can be retrofitted in the tunnel and, where necessary, replaced in sections, where the cross-section of the tunnel allows. The installation usually requires plugging and drilling activities that must not have an effect on the static of the building.

Furthermore it must be borne in mind that visual inspections[8] of the structure and therefore e.g. the identification of leaks are no longer possible. In the case of leaks there is the danger that panel and plaster systems could collect water and therefore end up weighing more and offering a reduced heat insulation capacity. Even with these systems, it is necessary to change elements and surfaces after a fire when a higher temperature has been reached. The inside supporting concrete construction that is usually not damaged in case of fire, does not need to be refurbished afterwards.

In addition, the reduced heat insulation capacity of fire protection claddings means that in the event of a fire more energy remains in the tunnel, which then needs to be removed in some other way e.g. through an effective fire ventilation system.

2.2.3 Support for the emergency and fire fighting services

Particularly high demands are made on emergency services when called to carry out rescues and fire fighting measures in tunnels. The emergency services personnel sometimes have to work under extreme conditions. For that reason it is essential to agree all safety measures with the emergency services in the design phase.

The time between alerting the emergency services and the initiation of measures at the accident site is relatively long in the case of incidents in longer tunnels. The focus of the emergency services is therefore not primarily on rescuing people from the direct area of danger. In this area the main emphasis is on self-rescue (see Section 2.2.1).

The fire ventilation is also operated as a supportive measure for the fire brigade in order to ensure that the smoke is removed in one direction. However this is only guaranteed up to a certain size of test fire. If the fire exceeds the dimensions of the test fire, a systematic extraction of the smoke or control over the flow of smoke is no longer possible, or on-

[7] Wire-mesh reinforcement is designed to fix the concrete in place mechanically and prevent it from falling, even if the concrete structure has been disturbed.

[8] DIN 1076 prescribes that as part of a major test of all parts of the structure, even places that are difficult to access must be tested in detail. Covers and claddings must therefore be removed.

ly to a limited extent. As the size of the fire increases, the advance of the fire brigade is also significantly hindered by heat radiation.

In order to speed up the fire fighting measures, tunnels longer than 400 m are equipped with a network of pre-filled (so-called wet) extinguishing water pipes. Here, too, it is necessary to ensure that the emergency services can get close enough to the source of the fire to carry out safe and rapid fire fighting measures. This can sometimes be done via the emergency exits.

Special equipment and vehicles are needed to cope with the special conditions found in tunnels. Further measures include the provision of fire brigade control panels in portal areas. A video surveillance system may be available and used for reconnaissance purposes.

Over a certain size of fire[9], however, no secure access to the site of the fire can be guaranteed for the emergency services. Fire fighting measures and rescues can only then be carried out when the fire load has burnt out to a certain level.

2.2.4 Reduction of economic costs and increase of operational availability

Among other reasons for its creation, the directive 2004/54/EG by the European parliament gives following statement: "…the latest tunnel accidents underline the importance of tunnels for human beings in terms of economic and cultural welfare…" Although still not fully regulated in many countries, the issue of economic costs in the evaluation of the effects of tunnel fires is growing increasingly important. This is in part due to the responsibility of the often public building contractor to use public funds sparingly, but also stems from the increasing number of public-private partnerships (so-called PPPs).

Tunnels often represent an important part of the infrastructure, and when they are out of action a considerable burden is placed on private and commercial road users. Traffic jams or diversion times give rise to high costs e.g. through lost working hours and longer transport times. This applies both to long tunnels and also for short underpasses at busy traffic intersections in inner city areas. Alongside the actual tunnel users other people, e.g. people living on diversion routes, are also affected when the traffic levels there rise sharply. This may also have a significant effect on the local economy. The directive 2004/54/EG states: "…tunnels of over 500m length represent an important infrastructure device, that connect major parts of Europe and that play an important role for the functioning and development of the regional economy…"

These factors play a particularly important role when there are only a few transport links, e.g. river crossings or where tunnels have been built to ease traffic congestion on other roads. The original infrastructure is then no longer in a position to cope with the rate of traffic.

Fire protection measures must be chosen such that on the one hand they limit the life cycle costs (LCC) to a reasonable level and on the other hand they protect tunnel users and maintain the highest possible level of operational availability for the users.

In the case of toll-operated tunnels, the direct consequence on toll incomes must be taken into consideration as well as the only indirectly quantifiable economic costs. Equally, in the case of privately financed projects fines are often imposed for periods of time in which the tunnel is not usable or only usable to a limited extent.

The availability of the tunnel must be maximised. Any downtime for repairs must be minimised.

2.3 Retrofitting of tunnels

The abovementioned protection targets apply equally to new and existing tunnel structures. For new tunnels the requirements valid at the time of construction are taken into consideration during the design phase. However, for older, existing structures, in particular, it must be assumed that the plans made several decades ago in specific circumstances will no longer comply with current safety requirements. New regulatory specifications, increased safety requirements or higher risks can make it necessary to retrofit existing tunnels. In such cases the improvements to the infrastructure and technical systems have to be balanced against the significant financial expense.

Examples are an increase in the fire resistance classification for the concrete covering that protects the reinforcement or a reduction in the distance between emergency exits. A revised increase in capacity for the fire ventilation system may also come up against significant problems caused by spatial restrictions. This means that such measures can often only be carried out at a very high cost.

[9] This level depends on the fire and the geometry of the tunnel, as well as other local conditions. According to the consortium a value of approx. 15-20 MW can be assumed.

2.4 Fixed fire fighting systems in tunnels

Measures that serve to improve safety can be divided into structural and operational or traffic-related measures. Many are firmly fixed in the regulations governing tunnels. Fixed fire fighting systems (FFFS), on the other hand, have only previously been specified in conventional building construction.

FFFS fight the fire itself, while other protective measures are aimed at reducing the effects of a fire or securing specified protection targets listed in Section 2.2 over a sufficient period of time. FFFS are not, however, designed to extinguish fires. Instead they aim to achieve the following physical effects that are described in more detail in Chapter 2.4:

- Limiting or reducing the size of the fire (Heat Release Rate),
- Slowing down or hindering the spread of fire,
- Reducing the radiant heat,
- Reducing the volume of combustion gases or hindering the backflow of the layer of smoke.

2.4.1 Types of system

The following explanations should be seen as general and simplified description to introduce the topic. A further detailed description was not intended here consciously to allow an explanatory description. Specific system types and technologies may vary in reality from the following descriptions. A choice and evaluation of a FFFS should be done based on full scale fire test data as well as specific system parameters.

Water mist systems

Water mist systems fight fire with water in the form of small droplets, of which 99% have a diameter of less than 1000µm [CEN 14972]. The droplets are created in special nozzles at a system pressure of up to 140 bar. The high pressure on the nozzle creates sufficient energy to split the water into fine droplets and to spray out these droplets. This serves to overpower the thermal levels of the fire (plume) so that the source of the fire can be reached[10]. The ventilation of the tunnel is used in this case to ensure a better distribution of the fine water droplets across the entirety of the tunnel cross-section. This means that even spaces under the tunnel ceiling can be targeted and concentrations of pyrolysis gases or fuel gases[11] diluted [LAK 2011].

The small water droplets have a very large (reaction) surface compared to a large body of water. This means that they are able to absorb a great deal of heat and evaporate in a very short space of time. The cooling effect of the ensuing droplets makes the steam condense away from the source of the fire. Since they have a larger reaction surface than bigger droplets from deluge systems the steam enthalpy (for water 2267 kJ/kg) in the area of the source of the fire is almost all used to absorb the energy of the fire. This increases the cooling effect and also reduces the amount of water needed compared to deluge systems.

Along with the cooling of the combustion gases and the ambient air, the water mist droplets absorb most of the radiant heat. This significantly reduces the temperature load for people and materials in the tunnel and limits the fire spread.

Wetting the fire load with water cools it down, which makes it less easy to ignite and slows down the combustion process.

According to NFPA`s “Fire Protection Handbook” water mist can be used to fight solid (Category A) and liquid (Category B) fires.[12] [FIR 2003] The burning liquid will not be spilled. [HÄQ2009]

The mist disperses rather like a gas, but the spaces under larger projections (e.g. under a damaged truck, in a hold or in a truck) are not reached directly Here, too, the effects of the fire can be fought effectively so that protection targets can be achieved.[13]

Fig. 1:
Activation of a water mist FFFS in a tunnel on the M30 in Madrid (Source: IFAB)

[10] The velocity is calculated by $V_{mean} = Q / A = Q / (\pi * r_{orifice}^2)$, see also [IFP2006] Magazine, pages 45 ff and NFPA [FIR 2003], Chapter 17 „Spray Characteristics“.

[11] In the case of leakages from vehicles with alternative fuel technologies flammable gases can accumulate in the space under the ceiling.

[12] Further explanations can be found at [NFPA 750] (p.37)

[13] During the UPTUN, SOLIT and SOLIT² tests it could be shown that the gas volume, gas temperatures and radiant heat even in case of covered fires could be reduced significantly. For further information refer to annex 2, [SOL2007], [UPT2006]

Measures to protect people from the extinguishing agent, water, are not necessary. The water used for extinguishing purposes does usually not contain any additives.[14] The system can therefore be activated as soon as the fire has been identified and located.

In the event of fire the parts of the FFFS themselves are also cooled by the flow of water and therefore protected from damage.

Water mist systems are generally simple to install, which means they offer high availability and good maintenance.[15]

Deluge systems[16]

Deluge systems also fight fire by producing water in the form of droplets. However, these systems can operate at a significantly lower pressure (usually < 10 bar). The droplets created are therefore much larger than in water mist systems and have a lower momentum.

The action principle of such systems basically consists of dampening the fire load with water. This cools the fire load and thus hinders ignition or stops the fire from spreading. The heating of the water droplets and, to a lesser extent, the evaporation of the water means that the water absorbs energy and therefore cools the air in the area around the spray. However the larger the droplets, the smaller the area affected, which means that the reaction surface is smaller in relation to the quantity of water. The combustion gases further away from the spray of water do not undergo a cooling effect. This low energy absorption in comparison to water mist systems means that conventional deluge systems need a water supply of 6 - 20 l/m²/min., depending on the application. [NFPA 502]

Fig.2:
Activation of an FFFS deluge system in Mount Baker Tunnel (I-90) in Seattle (Source: IFAB)

One constraint noticed by the members of the research consortium is apparent when fighting liquid fires. The atmosphere surrounding the fire is cooled but the fire might only be fought to a limited extent.

For further pro and contras it can be referred to the part of water mist systems if this applies also for deluge system, especially considering the high availability and relatively low maintenance costs.

Foam systems

For the purposes of this guidance, foam systems are considered to be those that use an extinguishing agent with an expansion ratio[17] greater than 4. For water mist and deluge systems that are used to improve the effectiveness of filming agents, e.g. AFFF or wetting agents, the system descriptions given in the previous sections apply. Compressed air foam systems are not subject of this guidance and are not described in any of the annexes.[18]

According to VDS the effectiveness of foam for fire fighting purposes is based primarily on the suffocation effect [VDS2108]. The fire load is covered with foam, which cuts off the supply of oxygen. According to observations made by members of the research consortium this can only happen in places within direct reach of the foam. In concealed areas, such as under trucks or inside vehicles, the foam has no or only very limited effect. As to water mist or deluge systems, similar restrictions have to be considered when fighting fire directly. The cooling effect of the fire load by using foam is being

[14] The investigations undertaken during the research project concerning water mist systems have shown that only one system uses AFFF as an additive. See annex 1.

[15] The set up is very similar to deluge systems. Please see the corresponding standard of VDS, NFPA, etc for maintenance and availability, The availability of the high presure watermist system in the EUROTUNNEL is as high as 99,982%. [FOG2012]

[16] In case of this Guideline the synonym for (open) sprinkler shall be used due to the similarities of operation of both technologies. The amount of water used in a deluge system is usually higher then in sprinkler systems.

[17] The ratio of the volume of the finished foam to the volume of the original foam-water solution.

[18] A manufacturer did not release recent test data concerning CAF-FFFS after a request by the consortium. A first assesment of this technology can be seen in the magazine "Tunnel", edition 05/2008, pages 58 ff, as well as [SIN 2005].

achieved due to the comprised water of the foam. The ratio between water and air has to be considered here. The structure is being cooled in the same way in the areas that are reached by the foam. The cooling of hot gases is minor compared to the before mentioned FFFSs due to the reason that less amount of drops tend to appear and as a result a smaller surface can be cooled. Following equation[19] describes the fact:

$$t_{vap} = \frac{D_0^{\,2}}{K}$$

$$K = \frac{(8 \cdot \lambda)}{(c_p \cdot \rho)} \cdot \ln\left[1 + (T - T_S) \cdot \left(\frac{c_p}{h_{vap}}\right)\right]$$

t_{vap} = Evaporation time [s]

K = Evaporation constant

D_0 = Drop diameter [m]

λ = Heat conductivity $[kJ \cdot s^{-1} \cdot m^{-1} \cdot K^{-1}]$

ρ = Density [kg·m³]

c_p = Heat capacity $[kJ \cdot kg^{-1} \cdot K^{-1}]$

h_{vap} = Evaporation enthalpy $[kJ \cdot kg^{-1}]$

According to foam additives safety data sheets [SCH2007] there is a possibility of hazard for human beings when being sprayed by foam. This effect has to be considered when evaluating a FFFS and the overall safety concept respectively the evacuation concept and the affront concept for fire fighters.

If the additive contains tensides, a slip hazard might remain. Depending on the foam texture obstacles and emergency exits might be concealed. Aspects of a barrier-free escape have to be taken into account. In case of strong foam inhesion a conciliation of warning signs for hazardous goods transports (according to ADR) and a conciliation of emergency exit indications has be considered.

If the before mentioned cases are likely to happen, it may be necessary to activate such a system not before every person has been rescued. The moment of activation (before or after evacuation) has to be adjusted according to the specifications of every single foam-FFS. Action forces of the rescue services have to be informed that warning signs and obstacles may be covered.

Shielding of the heat radiation is considered to be less compared to water mist and deluge systems due to the fact that less droplets are available to cool the heat radiation. [YU2011] [FÖR2012]

For the same amount of water in the space,

$N \sim 1/d^3, N = droplet\ number\ density$

$A_w \sim \frac{1}{d}, A_w = total\ droplet\ surface\ area$

The vaporization rate per droplet:

$$\dot{m}_d = 2\pi d\left(\frac{k}{C_p}\right)_g \ln\left(1 + \frac{Y_{d,surfacve} - Y_\infty}{1 - Y_{d,surface}}\right)$$

The total vaporization rate = $N\dot{m}_d \sim 1/d^2 \Rightarrow$

The smaller the droplet, the greater cooling and inerting

Thermal radiation transmission ~

$e^{-kf_v/d}, f_v = water\ volume\ fraction$

⇒The smaller the droplet, the greater the attenuation

Fig. 3:
Cooling and absorption of radiation Source: [YU2011]

According to [GRE2005], maintenance costs are high for foam based-FFS. There was only a limited amount of information of installed active protection systems in the tunnel available to the consortium concerning foam based-FFS. Due to this fact foam based-FFS are not taken into account any further in this Guideline.[20]

In international context the usage of foam based-FFS can be seen as an exception.

[19] [GAN 2002]

[20] During the research period only one rail tunnel could be identified using a foam based-FFS. Other installation or planned installations are not known. Fire tests are unknown as well.

One prototype installation and one planned project could be identified using compressed air foam. This technology is not being examined here. Further projects in which compressed air foam-FFFS are foreseen as alternative could not be identified. (See Annex 1 for further details). The only tests with compressed air foam which could be identified were carried out back in 2005. However, not one single installation matching the tested technology could be identified.

2.4.2 The effect of FFFSs in tunnels

The following statements are based only on water based FFFS.

The effective mechanisms of FFFSs in tunnels are explained and illustrated below using results from full scale fire tests. The graphs are based on measurement data from fire tests in the SOLIT² project as well as other fire tests also in a 1:1 ratio, such as the predecessor project SOLIT or the tests carried out for Eurotunnel as part of the SAFE project. For the comparative graph, however, measurement data from tests using an FFFS (left) are shown against the corresponding data without the influence of an FFFS (right). The "without FFFS" scenario uses the accepted fire curve calculation or genuine data from real fire tests, such as the tests carried out in the Runehamar – Tunnel in 2003 [ING 2011].

An evaluation of the effectiveness of a FFFS, as with any other tunnel safety measure, must be carried out by comparing the corresponding parameters both with and without the application of an FFFS or other protective measures. The overall effectiveness of all measures must always be taken into account. An examination of individual factors does not achieve the same target.

Data from fire tests for the case with FFFS vary considerably according to the type of system used. The data must therefore always be calculated on a system-specific basis (dependent on type and manufacturer). The following genuine data are based on the water mist systems used as part of the SOLIT² research project and should therefore be seen as purely exemplary. The systematics, however, can also be applied to other types of system on the basis of fire tests in a 1:1 ratio.

2.4.2.1 Temperatures and radiant heat

To evaluate temperatures both the convective heat transfer and the radiant heat must be taken into consideration. The latter plays a major role in the direct proximity of the fire.

Furthermore, the time period is of major importance when evaluating the impact of the exposure.

The duration of the effectiveness is also relevant when evaluating the load.

The temperatures are significantly lower than in the case of free combustion. In particular in the case of real measured data in the direct proximity of the fire it must be borne in mind that a mixture of convective temperature and radiant heat is always shown and the measured temperature is therefore generally higher than the actual convective ratio. The key factor for the impact on the structural part is the temperature of the material or the surface.

A further example is the significantly higher cooling potential of an FFFS at a distance of 20 m in the flow direction from the source of the fire.

If no FFFS is used then a temperature level up to four times higher can be found 20 m behind the source of the fire. In the case of the fire tests in the Runehamar Tunnel temperatures of over 100 °C were measured even at a distance of 458 m.

Temperature levels with FFFS

FFFSs in tunnels can reduce the maximum temperatures reached. This means that the potential temperature reduction is significantly influenced by the location and the type of system.

The following graph shows the temperature in the direct proximity of the fire for a truck fire scenario.

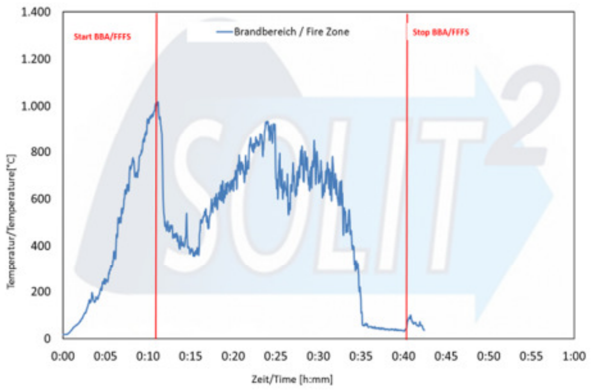


Fig. 4:
Air temperatures immediately above the source of the fire in the case of a truck fire with activated FFFS

Temperature levels without FFFS

A fire curve calculation can be applied to the area around the source of the fire. Fire tests have shown that the ZTV-ING curve or the RWS curve can be considered to be realistic.

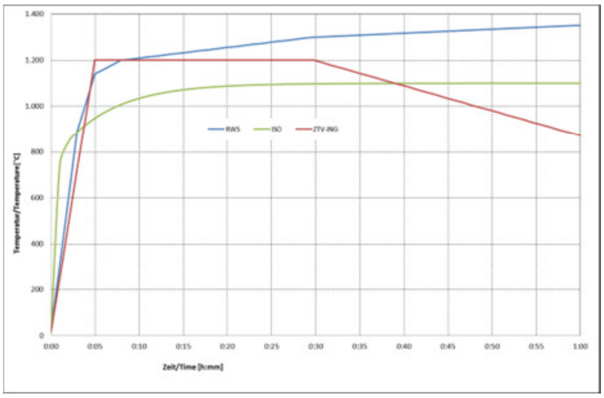


Fig. 5:
Comparison of the RWS, ISO and ZTV-ING curves

Fig.6:
Schemtic view of area with high temperatures during a truck fire with FFFS

Fig. 7:
Schemtic view of area with high temperatrues during a truck fire without FFFS

Temperature levels with FFFS	*Temperature levels without FFFS*

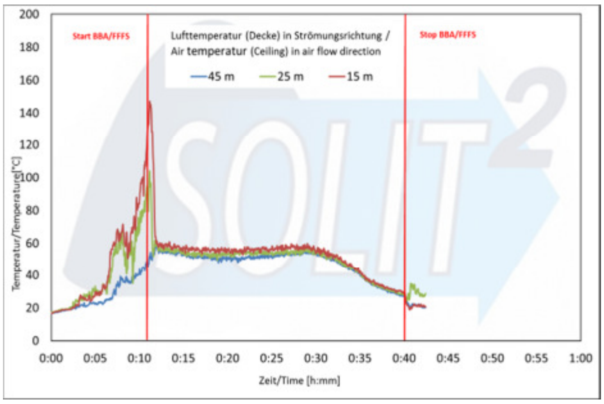


Fig. 8:
Temperatures across the cross section of the tunnel at various distances during a fire test with a truck fire and activated water mist FFFS

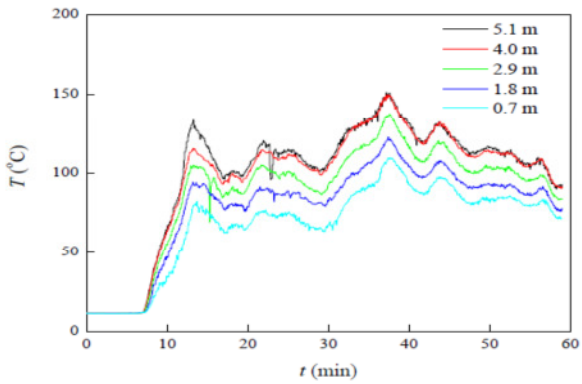


Fig. 9:
Temperatures across the cross section of the tunnel at a distance of 485 m during a fire test with a truck fire [ING 2011]

Duration and area of high temperatures with FFFS

Basically when a FFFS is used it cannot be assumed that the FFFS will extinguish the fire. However, through the encapsulation of the fire source the impact and the duration can be limited significantly. Due to an early access of the fire brigades this effect can be further assisted.

This also applies to liquid fires, which can be partially or totally concealed. However, the duration of the effect in the case of liquid fires is of minor importance, as it can burn out quickly, but as described in Section 2.5.4 the duration of the fire is limited by the combustible material. Moreover, the fast discharge of the liquids (usually there is a slit drainage gutter at the side of the tunnel) reduces the burning time.

In the case of solid fires the fire progression and fire spread are slowed down considerably. Tests using truck fires consistently showed that only one part of the fire load burned. This means that the duration of the effect of high temperatures on one individual place was significantly reduced.

Duration and area with high temperatures without FFFS

Without an FFFS a fire can spread in a rapid and uncontrolled manner. This means the fire may spread to neighbouring objects. This is reflected in the ZTV-ING and RWS curves. For tunnels with a high risk potential the effect is likely to last even longer.

Since the spread of fire cannot be hindered and there is no cooling of the hot combustion gases, it can be assumed that the high temperatures will have a large-scale, long-lasting effect on the tunnel and the people inside.

Duration and area of high temperatures with FFFS

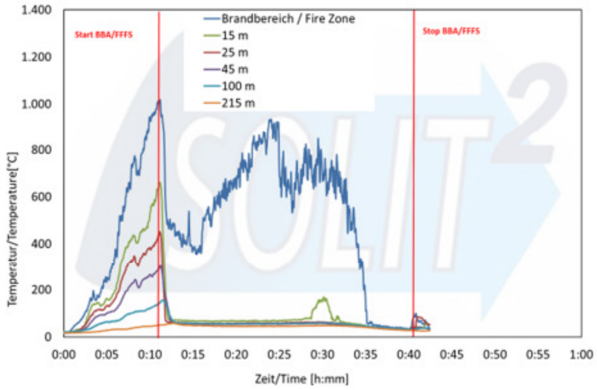


Fig. 10:
Ceiling temperatures at various distances from the source of the fire in the direction of the flow during a fire test with a truck fire and an activated FFFS

The spread of the fire to neighbouring objects is generally hindered so that only the initial site of the fire is affected. This means that an FFFS may not completely prevent higher temperatures but the effect is limited to a short period and a smaller area (usually in the direct proximity of the flames).

Water mist systems in particular have a high potential of absorbing radiant heat due to the small size of the water droplets.

Duration and area with high temperatures without FFFS

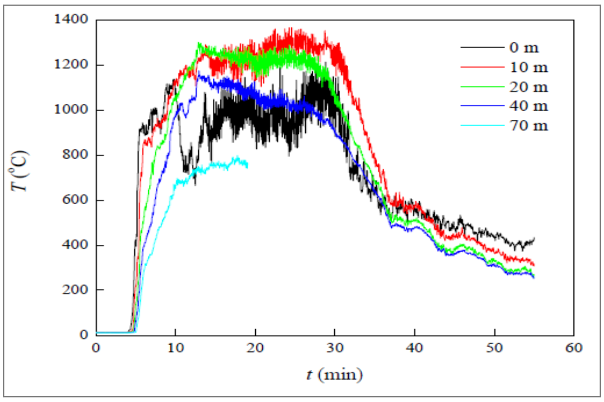


Fig. 11:
Ceiling temperatures at various distances from the source of the fire in the direction of the flow during a fire test with a truck fire (Source: ING 2011)

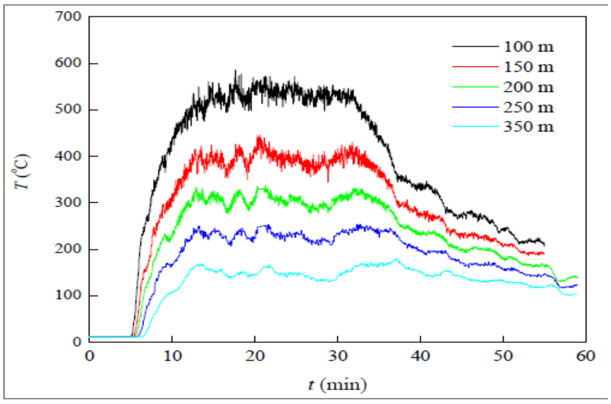


Fig. 12:
Ceiling temperatures at various distances from the source of the fire in the direction of the flow during a fire test with a truck fire (Source: ING 2011)

Radiant heat levels with FFFS

Depending on the type of system, an FFFS can significantly reduce the radiant heat e.g. for the tunnel infrastructure or the emergency services.

This is clearly shown when one sees how close it is possible to get to a large fire with an activated FFFS.[21]

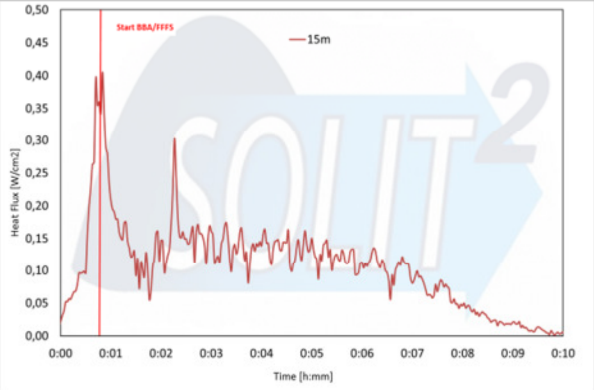


Fig. 13:
Radiant heat during a fire test with a truck fire at 15 m distance from the fire and 1.5 m height

Radiant heat levels without FFFS

The level of radiant heat generated without an FFFS is hard to estimate. Reports from real incidents document that the high radiant heat made it impossible to get closer than 50 m to the source of the fire and that the fire spread over more than 80 m as a result of the radiant heat. [DUF 1999]

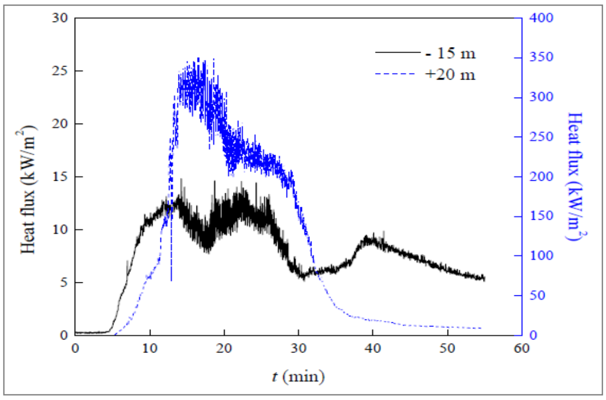


Fig. 14:
Radiant heat during a fire test with a truck fire load (Source: ING 2011)

[21] During fire tests with a 60MW fire and with proper fire protection clothes it was possible to access the fire up to 1,5m from the upstream side.

Duration / spread of fire with the application of an FFFS

An FFFS is able to significantly slow down the fire progression and to prevent the fire from spreading e.g. to the next truck.

The fire brigade emergency services can reach the source of the fire far more quickly, making it easier to fight and extinguish the blaze. This means that the fire does not carry on burning for nearly as long.

During fire tests the efficiency of an FFFS in preventing the spread of fire is tested along with other fire objects (target fire loads), placed behind the source of the fire in the direction of the air flow.

Duration or spread of fire without the application of an FFFS

Without the use of an FFFS the fire spreads rapidly and also spreads onto other objects.

In the case of fires in tunnels a fire spread of up to 450 m has been reported due to radiant heat and high temperatures [DUF 1999].

Even though a fire that lasts for 56 hours, as was the case with the fire in the Mont Blanc Tunnel, is an extreme example, the fire can always be expected to last significantly longer. This effect is strengthened by the fact that the fire brigade can only access the source of the fire with great difficulty.

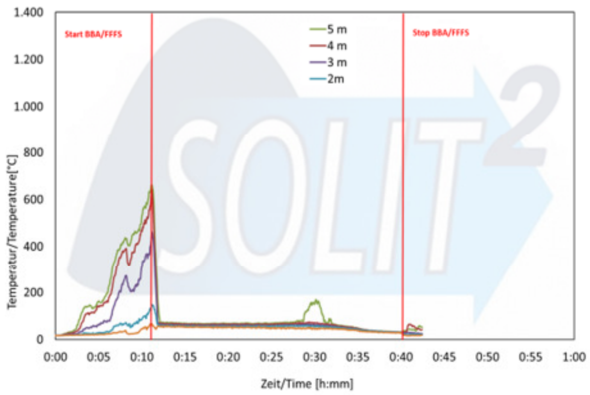


Fig.15:
Temperature on a target[22] at a distance of 5 m in the direction of the air flow from a truck fire with activated FFFS

Fig. 16:
Spread of fire to a further object at a distance of 5 m during a fire test without FFFS

[22] The target is used to assess if there is a spill-over of the fire.

2.4.2.2 Duration or spread of fire

In general FFFSs for tunnels are not able to completely extinguish a fire. An FFFS in a tunnel situation is designed to limit and reduce the effects of a fire and to slow down the spread of the fire. The complete extinguishing of the fire is the responsibility of the fire brigade. Here it is crucial to enable them to act quickly and safely.

Heat Release rate (HRR)

The HRR is an arithmetical and theoretical value which can be used to estimate the effects of free combustion. The information provided by a HRR on its own, however, cannot determine the amount of combustion gases, temperature and gas concentrations that may arise. This must always be evaluated together with environmental conditions, the cross section of the tunnel, the type of fire load(s) and, where applicable, the use of an FFFS.

Previously it was often assumed that the effectiveness of an FFFS could be assessed by measuring the HRR. Extensive analysis of a large number of fire tests shows that this is not the case, or only partially so.

When an FFFS is used the height of the HRR cannot be used to determine parameters such as temperatures, behaviour of combustion gases or other effects in the tunnel. The HRR is therefore not suitable for use as a primary measuring device to evaluate the effectiveness of an FFFS. Rather, other parameters should be used, such as the reduction of the volume of combustion gases, the drop in temperatures, the reduction of radiant heat.

At the same time it must be taken into consideration that the current measurement and calculation processes (e.g. following the oxygen consumption method) to determine the HRR only apply to uninfluenced fires and therefore when it comes to fire tests with FFFS there is less precision and greater dispersion [STA 2007].

Basically, the progression of the HRR is critically influenced by the composition of the fire load and the ventilation conditions. In the case of larger fires in tunnels it can be assumed that these are heavily influenced by the ventilation. A higher longitudinal ventilation rate provides the fire with more oxygen and the HRR therefore goes up.

HRR development with FFFS (solid fires)

The progression of the HRR depends on the composition and arrangement of the fire load. When the fire load is covered (with e.g. a tarpaulin) the opportunity to fight the fire is delayed. As can be seen in the figure below and as shown in fire tests, the use of a FFFS interrupts the progressive increase of the HRR and limits its highest level.

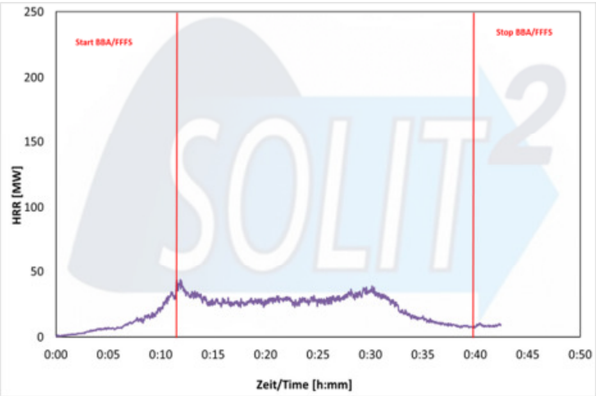


Fig. 17:
HRR with a truck fire with a covered fire load and activated FFFS

HRR development without FFFS (solid fires)

The progression of solid fires can go very quickly in some circumstances. The SAFE-Station tests have shown that within a few minutes after the fire has started a HRR of up to 200 MW can be reached.

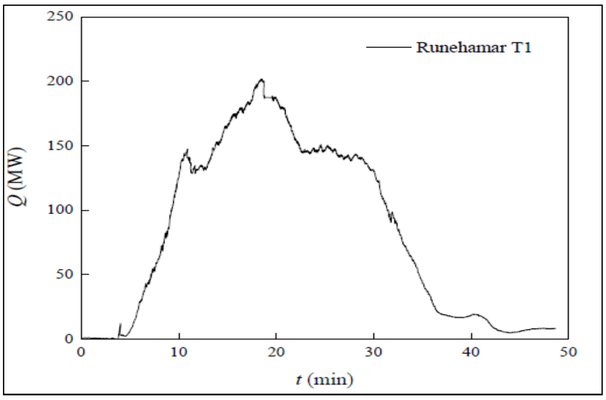


Fig. 18:
HRR with a truck fire with covered fire load [ING 2011]

HRR progression with FFFS (liquid fires)

Open liquid fires can be successfully fought with most FFFS, and in some cases even partially extinguished. In practice, however, this is very seldom the case, as pools of liquid can also be concealed by vehicles. This is why the primary effect of an FFFS here, too, is in the containment and reduction of the effects of the fire.

Since liquid fires progress very rapidly and can also overrun other flammable goods, it is essential to ensure the fastest possible activation of the FFFS.

HRR progression without FFFS (liquid fires)

Liquid fires develop far more rapidly than solid fires. However, even with liquid fires there tends not to be an abrupt ignition of the surface of the liquid. Furthermore in reality there is likely to be some kind of limiting factor to the surface of the liquid, as liquids can only spread so far thanks to the presence of slit gutters etc.

The research consortium did not get to know from any major fires in tunnels where large areas where affected by burning liquids.

2.4.2.3 Progression and spread of combustion gases

When evaluating the progression of combustion gases a clear distinction must be made between visible smoke, in other words the particles, and toxic gases. The spread of the smoke is considerably influenced by the ventilation concept. The evaluation of toxicity and visibility is examined in more detail in Section 2.4.3.

Progression and spread of smoke with FFFS

In a large number of test fires the limitation of HRR also reduced the development of combustion gases. The cooling effect of the FFFS also reduces the volume of combustion gases. As a result an existing e.g. already installed capacity for fire ventilation can help to control the smoke production of a (theoretically) far larger fire than would be the case without the cooling effect of an FFFS. Due to the impulse of the water and the cooling of the gases a turbulent stream may arise, leading to a partial destruction of a smoke layer. The construction of fans and smoke channels can be adjusted to suit the lower temperatures.

Even when water-based FFFSs wash away some of the combustion gas elements in particle form, this effect is negligible.

Progression and spread of smoke without any FFFS

The rapid fire progression in liquid fires, and also with solid fires, means that immediately after the outbreak of fire there is a strong build-up of combustion gases. The considerable turbulence in the tunnel, caused by the longitudinal flow and the vehicles inside the tunnel, means that there is a real danger that the layer of smoke will soon be disturbed or will not build up in the first place.

At the same time it must be borne in mind that ventilation systems usually need a few minutes to reach full capacity. This is particularly unfavourable in the case of rapidly developing liquid fires.

Fig.19:
Disappearance of the smoke layer with activated FFFS

Fig. 20:
Layer of smoke in a 30 MW liquid fire shortly after ignition.

2.4.3 Evaluation of the suitability of an FFFS for a specific tunnel

In order to assess the suitability of an FFFS for a specific tunnel the first step is to define the protection targets for the tunnel in question. The individual protection targets are achieved in fundamentally different ways through the different system technologies and types. The protection targets vary in importance, depending on the tunnel. This is why case-by-case tests are required.

Alongside the effect of the FFFS, the interaction of the system with other protective measures must be evaluated: in other words, the entire system. This means that in order to evaluate the suitability of an FFFS the degree of negative effect the fire will have on the tunnel users, emergency services and the structure itself are of crucial importance. It is not just the level of a load (e.g. temperature, toxic gases) that must be considered but also the duration of the exposure.

The suitability in terms of achieving selected protection targets is described in the following, giving the example of a water mist system. As already described in Section 2.4.2 this is a fundamental systematic, which can be used for other types of system when test data from fire tests measured by real standards is used.

2.4.3.1 Self-rescue

The conditions for the self-rescue of people in the event of a fire are primarily determined by the following factors, in which the load factors in their entirety act together in a complex interplay, with different effects on different people:

- Temperatures at breath height
- Concentrations of toxic gases at breath height
- Visibility or orientation ability

Temperatures at breath height

The following diagram shows the progression of temperatures in a truck fire. It is clear to see that directly behind the location of the fire the use of an FFFS means that a sufficient temperature level can be maintained (see. fig. 53) to produce a survivable atmosphere. This is particularly clear in 458 m behind the source of the fire even higher temperatures were measured than directly behind the source of the fire with an activated water mist system.

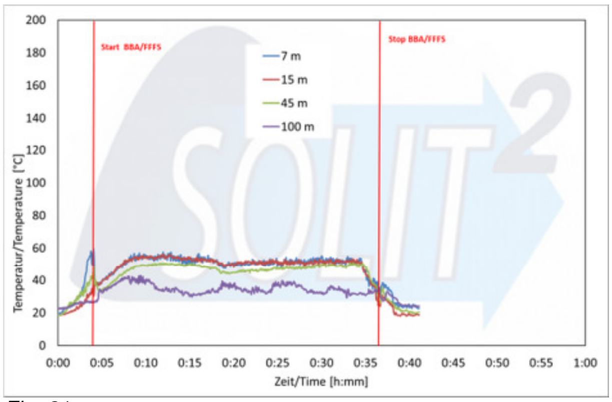


Fig. 21:
Temperatures in 2 m height at different distances in the direction of the air flow for a truck fire with activated FFFS

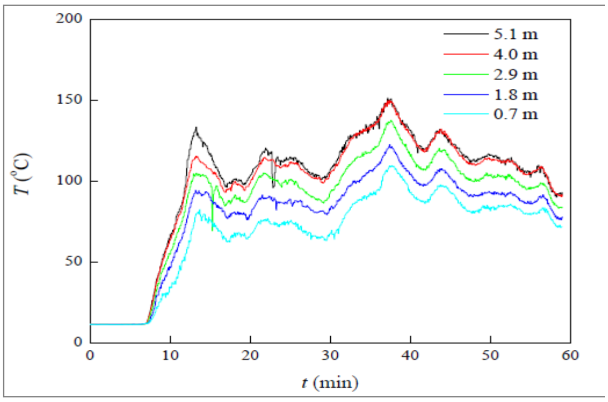


Fig. 22:
Temperatures in 458 m distance for a truck fire. The temperature at 1.8 m height can be used as a comparison with (Source: ING 2011)

Similar results can be seen with liquid fires (test fires). This is shown below in the example of a 50 MW liquid fire with and without activated FFFS.

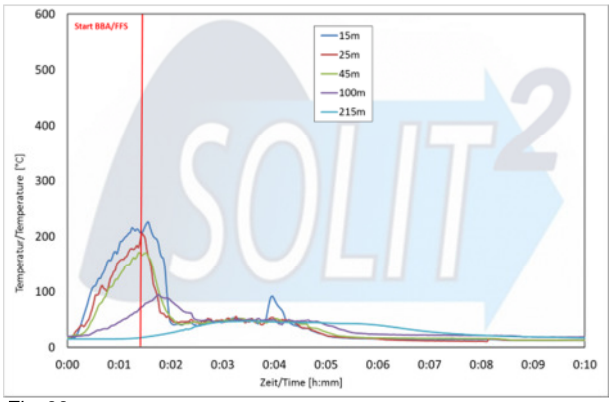


Fig. 23:
Temperature at 2 m height at different distances in the direction of the air flow for a liquid fire with activated FFFS

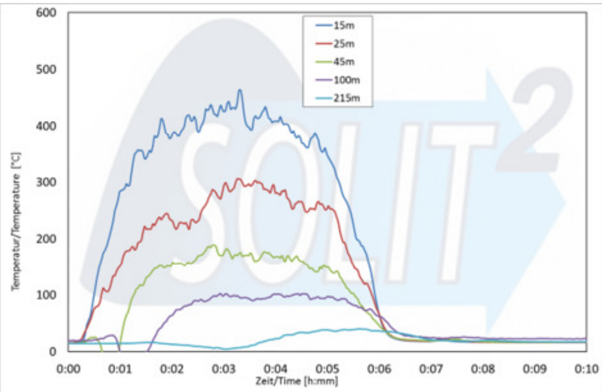


Fig. 24:
Temperature at 2 m height at different distances in the direction of the air flow for a liquid fire without activated FFFS

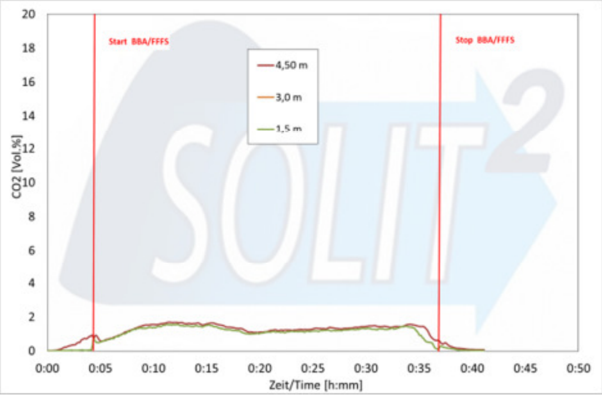


Fig.25:
CO_2 concentrations for a truck fire with activated FFFS at a distance of 45 m

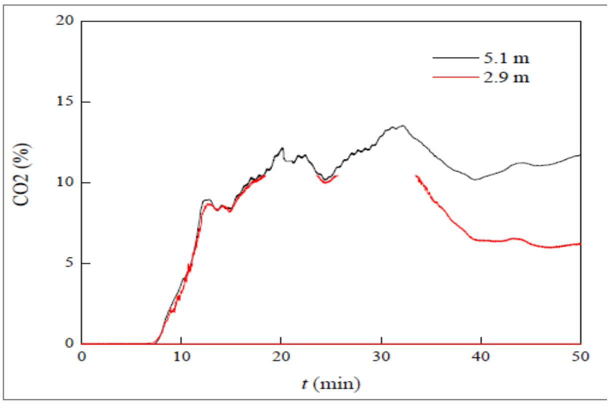


Fig.26:
CO_2 concentrations for a truck fire at a distance of 458 m to the source of the fire (Source: ING 2011)

Concentration of toxic gases at breath height

The suitability of measures that are aimed at maintaining a survivable atmosphere in terms of the concentration of toxic gases must be evaluated according to the fire ventilation concept.

The use of longitudinal ventilation can lead to turbulence of the combustion gases across the cross section of the tunnel behind the source of the fire in the direction of the air flow. This happens regardless of whether an FFFS is used.

When using ventilation concepts that are based on a possible layer of smoke there could equally be turbulence across the entire cross section of the tunnel, but limited to the area in which the FFFS is activated. In the case of large fires it can also be assumed, therefore, that turbulence will affect the smoke even without the use of an FFFS, and that this could also reach well beyond the location of the actual incident.

In general, when making a comparison with ventilation concepts it must be borne in mind that it can take several minutes for a fire ventilation system to achieve full capacity.

When an FFFS is activated the HRR is limited and this leads to less smoke being produced. This means that a survivable atmosphere can be maintained for longer.

This shows an example of the comparative measurements of carbon dioxide (CO_2) concentrations. Without the use of an FFFS a level is soon reached that would be fatal for humans in a very short space of time.

Orientation ability

The ability to orientate oneself in the tunnel plays a major role in the evacuation. The orientation ability is significantly affected by visibility, but also by aids to orientation (escape route markings). Orientation ability is indicated, alongside many other influences (age, mobility, constitution, condition of evacuee, time of day etc.), predominantly by the speed of the escape.

The introduction of the extinguishing agent (water mist in this case) can affect visibility. For the effects on the combustion gases please refer to Section 2.4.3.1. Through fire tests in test tunnels and by activating FFFS in genuine tunnels without fires it has been possible to show [SOL 2007] that a well-planned escape route (e.g. according to RABT, every 25m) marking system and appropriate lighting provide sufficient orientation for self-rescue to take place without a delay.

2.4.3.2 Emergency rescue and fire fighting measures

In principle the same criteria apply to emergency rescue as self-rescue. However, the emergency services have protective equipment, are properly trained. They can therefore remain able to operate even under more critical conditions. The basic criteria for this are:

- Temperature and radiant heat at breath height
- Orientation ability
- Protection from spalling or falling masonry

The toxicity of the combustion gases is less of an issue for the emergency services as they have breathing apparatus, although this only operates for a limited period of time.

Fig. 27: Firefighter in the direct proximity of a truck fire with activated water mist system

Temperature and radiant heat at breath height

Unlike self-rescue, where people distance themselves from the source of the fire, in the case of emergency rescue the temperatures surrounding the burning area and the radiant heat play a much greater role.

The comparison of the temperatures with and without activated FFFS show very clearly that without a FFFS the high temperatures mean that it is often not possible to approach the source of the fire against the direction of the air flow or to work at the source of the fire. The tactics of the fire brigade normally assume that the fire will be approached in the same direction as the air flow.

The limiting factor here is the radiant heat generated by the fire. Reports based on practical experience show that in the case of larger fires it was not possible to approach to distances below 50 m, even in the direction of the ventilation, without the intervention of an FFFS. With water mist systems, on the other hand, the high cooling effect and the absorption of the radiant heat make it possible to approach very close to the source of the fire.

When selecting the system technology care should be taken to consider that there is no additional risk to the emergency services e.g. by covering the floor surface, or due to an increased risk of slipping.

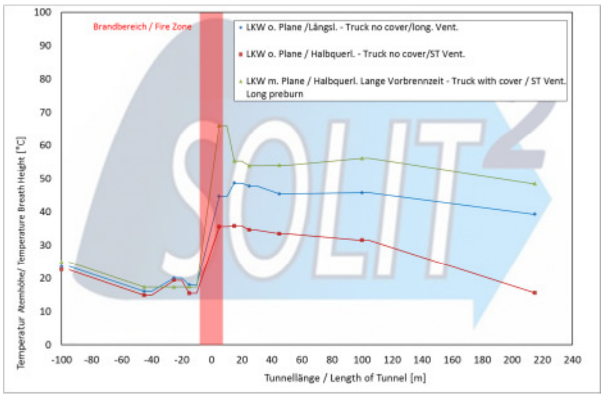


Fig. 28:Temperature distribution at breath height near a truck fire with activated FFFS and different ventilation concepts

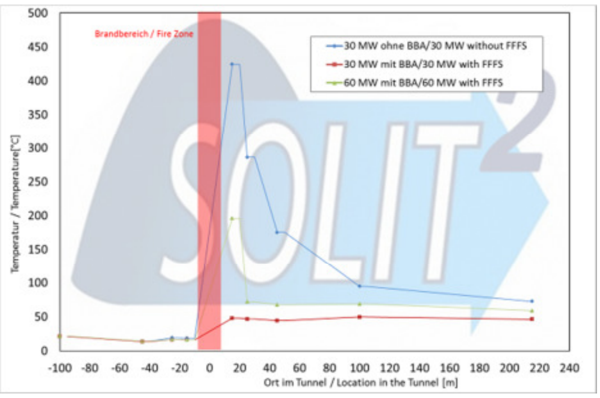


Fig. 29:Temperature distribution at breath height near a fire (Category B) with and without activated FFFS

Orientation ability

Even when the emergency services are appropriately trained in order to be able to orientate themselves in smoke and other unfavourable visibility, the best possible visibility should be a priority for the emergency services in the fire fighting phase. With longitudinal ventilation systems it can be assumed that in the direction of the air flow there will be zero the visibility will be zero in all cases. However, emergency services have reported that activated FFFS have improved orientation ability because the smoke has been brighter.

Since in the worst case scenario there may be a fully developed fire burning during the emergency rescue phase, the size of the fire may well exceed the test fire set for fire ventilation purposes. The emergency services are also likely to come across massive hindrances. As explained in more detail in Section 0, the activation of an FFFS increases the efficiency of the fire ventilation through its great cooling effect and this can therefore be expected to lead to an overall improvement in visibility. A considerable improvement in visibility is therefore

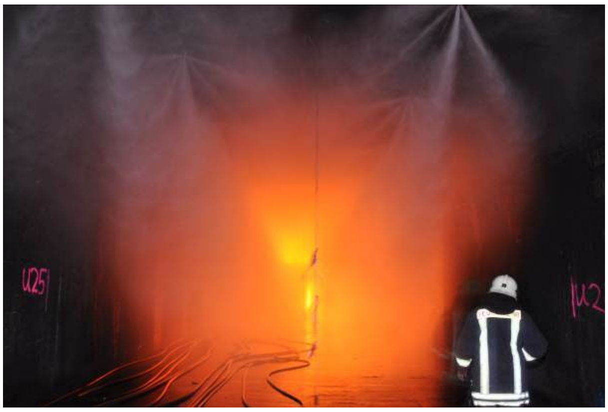


Fig.30:
Typical view of a fire fighter looking at the source of the fire (approx. 40 MW) from a distance of 20 m with an activated water mist extinguishing system

to be expected. The area of the activated water mist system can suffer from a certain reduction of visibility. However this is usually above that which is to be expected where no FFFS is available.

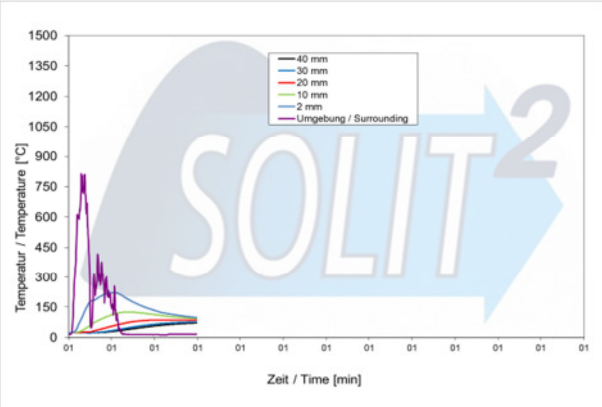


Fig. 31*:*
Temperatures in a concrete sample during a fire test with a truck and activated FFFS

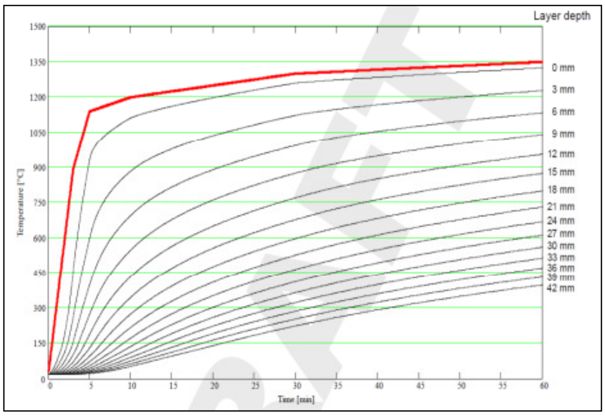


Fig.32:
Temperature progression in different depths of concrete using the RWS curve

Protection from spalling or falling masonry

The load of the tunnel structure is determined by the temperature that is transmitted by radiant heat and convection. It is fundamentally affected by the relevant height and reaction time. If it is possible to reduce these two factors, the thermal load of the structure will also be limited. The risk of spalling and other damage to the structural condition of the concrete declines dramatically. Emergency services will be better protected from injury through spalling or falling structural elements.

The clear reduction of temperatures and radiant heat as well as a shortening of the reaction time compared to a free combustion or the commonly applied fire curve calculations has already been discussed in Section 2.4.2.1. When the effect inside the test bodies is examined, it becomes clear that the progress of the heating inside the structural element is significantly slowed down.

2.4.4 Use of FFFS with hazardous goods

The probability of hazardous goods being involved in a fire is extremely low (see Section 2.5.1). However, since the release of hazardous goods is expected to produce large-scale damage, this event in a tunnel space deserves special consideration. European agreement on the road transport of hazardous materials, [ADR 2011], foresees restrictions on hazardous goods transportation in tunnels depending on the level of danger. Certain hazardous goods are not allowed in some tunnels in Germany, according to the risk-based method for categorizing road tunnels according to ADR [BAL 2009], because they do not meet the safety criteria, even though the equipment complies with the directives. Often it is the transport of flammable liquids (Class 3) which is decisive for categorisation. When FFFS are used, the effect of hazardous spills must be taken into account.

Interaction between hazardous materials and FFFS

In particular, fires with the most common hazardous goods of Class 3 may very well be controlled in case of fire by water-based FFFS. This effect can be further enhanced by the use of AFFF (Aqueous Film Forming Foam, AFFF). Water also serves to dilute any hazardous substances.

Interaction of hazardous goods and FFFS

Especially fires of class 3 hazardous goods (which are most the most frequent hazardous goods) can be controlled very well by water based FFFS. Using AFFF the effect can even be improved. Moreover, water has a diluting effect to many hazardous goods.

Only hazardous goods which have an exothermic reaction in contact with water must be regarded critically. It should be noted that for this to happen the substance must leak, and the transport container must therefore be damaged. Further investigations [LAEM 2009] have shown that while an exothermic reaction occurs in the immediate vicinity of the substance, its effects are controlled by the FFFS in a fire.

For all fires involving hazardous goods, the intervention of the fire services is essential. In a major fire in a tunnel without an FFFS however, prompt and safe access to the fire would be almost impossible, and thus there would be little opportunity to check the presence of a hazardous goods vehicle.

Influence of an FFFS on the release frequency

For the required risk-based review of hazardous release scenarios, the frequency is of great importance. A distinction must be made between primary and secondary releases, where the incidence of secondary release is considerably higher:

- primary releases, in which a technical defect in the transport container or a heavy collision leads to the hazardous material being released and igniting with combustible material.
- secondary releases, in which a technical defect in the transport of hazardous goods vehicle or a collision of the transporter itself or next to it, leads to a fire breaking out which can develop unhindered and spreads to the hazardous substance.

In primary releases an FFFS as described above has a cooling and controlling effect; however very large events are almost impossible to control.

If however dangerous substances are released only as the result of another initial event (secondary release), the release of the hazardous substance can be prevented or significantly delayed by the use of a FFFS, thanks to its cooling and prevention of flashover. Consequently, the risks posed by hazardous goods itself is reduced by the substantial reduction in the frequency of occurrence. In particular, substances which react exothermically with water do not usually come into contact with water when an FFFS is used. If this nevertheless should be the case, exothermic reactions could not be avoided. However, the FFFS provides cooling and shielding of thermal radiation, facilitating the intervention of the fire service.

Especially in critical tunnels, the use of FFFS can prevent the categorisation and with it the limitation of hazardous goods transport, and significantly increase the security of tunnels without limitations for hazardous goods transport.

2.5 Design fires for dimensioning fire protection equipment

2.5.1 Basic principles governing design fires

The test fires described in the following sections have been chosen to cover all significant large fire load cases relevant for the components or technical equipment, so that most real fires can be controlled. The test fires are based on fire development, as observed as having a high probability of occurring in reality.

Fires not involving hazardous materials

Based on the cause of the fire, two basic characteristics of fire development can be distinguished.

By far the largest share corresponds to the classic fire development. This develops relatively slowly in the beginning and increases rapidly only in the so-called flash-over phase to full fire. On the other hand, this leads, exclusively in the case of liquid fires, which may occur in the form of pool fires immediately after ignition, to a very rapid development of the fire. Fig. shows the characteristic fire development and its frequency distribution.

Even though very fast developing fires that reach their maximum temperature and energy release in a short time are very rare, they may be the decisive scenario for the design. It should be noted here that in fire tests several attempts are often needed to ignite the pan. These fires are not directly comparable with pool fires. Further explanatory notes on this topic can be found in Section 2.5.4.

Fires involving hazardous materials

Approximately 5% to 6% of goods traffic on the road involves hazardous goods. Hazardous goods fires develop in essentially the same way as conventional fires. In the case the fire development may be considerably faster and the energy release may be much greater than in the case of fires with no hazardous materials.

In the case of combustible hazardous goods, the following additional scenarios must be included in a probability analysis and in the evaluation of the effects.

- The type of hazardous goods must be considered.
- The hazardous goods vehicle is not involved in the accident. An uncontrolled fire (without a FFFS) may then lead to an involvement.
- The vehicle is involved in the accident. The hazardous goods are not released. Lack of fire control may lead to the spread of the hazardous goods.

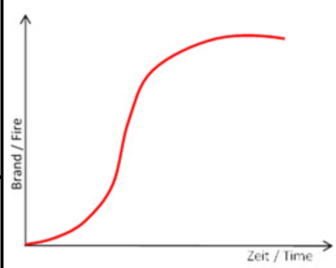
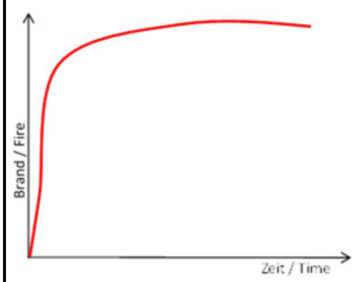
Fires without Dangerous Goods according to ADR	Fires per km and Year	Fire Rate	Distribution	Example Cause	Frequency (Assumption)	Characteristic Fire Curve
Fires cause by technical faults (without Entry/Exits)	3,68E-09	3,00E-09	81,5%	Hot Breaks, Fire of Tyres, Cable Fire, Turbo-Charger over-heated	100%	
Fires caused by collisions (without Entry / Exits)		6,84E-10	18,6%	Short-circuit in the engine compartment	majority	
				Spontaneous leaking Oil or Gasolin, which could ignite on hot vehicle parts	very seldom	

Fig.33:
Overview of frequency of fire curves related to the cause

- The hazardous goods are released and ignited.
- The fire spreads from the hazardous goods.

The usual test fires do not consider the involvement of hazardous goods, due to their low probability and thus the uneconomic or technically non-feasible measures for their control.

2.5.2 Design fires to determine the size of passive fire protection measures

The dimensions of constructions and the corresponding passive fire protection measures are determined using time and temperature curves. In Germany the so-called ZTV-Ing. curve is used. Other well known curves include the Dutch RWS curve, which has also been adopted by other regulations, such as the NFPA 502.

These curves represent the time-dependent temperatures, which could have a potential effect on the structural element if a fire were to develop rapidly. The size of the fire is not defined.

When selecting or modifying the time/temperature curves the important factors are the temperature and the time taken to reach it, along with the duration of the effect of the temperature on structural elements.

Under certain conditions it is possible or essential to modify the existing standard curves. Where a particular risk is present it may be essential e.g. to extend the duration of the effect.

By using an FFFS, the presence of the relevant verification can lead to an assumption that the reaction time and/or the maximum temperature will be reduced. The effects on the specifications for structural elements and their stability can then be reassessed. More about this process can be found in Section 3.2.3.

2.5.3 Design fires to determine the size of fire ventilation systems

Fire ventilation is designed exclusively to keep the tunnel and escape routes free of smoke during the self-rescue and emergency rescue phases.

In order to calculate the necessary fire ventilation, RABT 2006 and other regulations give maximum fires sizes of 30–100 MW [23] as well as the corresponding amounts of combustion gases released[24]. However, it must be noted that these test fires do not represent the maximum size of fire and therefore quantities of smoke that can be expected; instead they only cover a certain percentage of fire incidents (either maximum size of fire or time until the HRR is reached) that could occur in the specific tunnel.

Furthermore, when evaluating the effectiveness of fire ventilation it is important to note that the design and dimensioning of the fire ventilation is generally done using model calculations. Here it must be noted that the application of model calculations to determine the dimensions of fire ventilation systems is only validated to a limited extent by fire tests carried out in a 1:1 scale. Various realistic fire tests in the framework of SOLIT and SOLIT² have shown that for example a stable layering of the combustion gases over larger distances cannot always be achieved, even with a mathematically correctly dimensioned combustion gas extraction system, even though that is what could have been expected according to previous estimates. This is particularly the case with larger scale fires (> 30 MW), depending on the cross section of the tunnel. The reasons for this include the considerable levels of turbulence generated by the fire itself or as a result of the vehicles standing in the tunnel.

The use of an FFFS can increase the effectiveness of a particular fire ventilation system, or disperse a particular quantity of smoke with a smaller ventilation capacity. It may not be necessary to install a smoke extraction system above a false ceiling. Due to the different influences on the fire and on the temperature of the combustion gases, and therefore on the volume of smoke, a reduced fire design calculation can be implemented in the design stage. A description of the process, verified by the use of real data, can be found in Section 3.2.1.

2.5.4 Fires scenarios for dimensioning FFFS

The latest technology only allows the effectiveness of FFFS to be tested using fire tests carried out using realistic criteria. However, it is not necessary to test the effectiveness separately for each tunnel, as the data can be extrapolated and interpolated within certain boundaries.

It has however been shown that across-the-board system parameters, such as water exposure rates, are not enough to evaluate the effectiveness of an FFFS in tunnels. In terms of experience-based values, such as those used for deluge systems in

[23] Generally dependent on the density of traffic or the truck capacity

[24] To calculate the extraction capacity required the quantity of combustion gases is increased with a mixing factor that is dependent on the longitudinal flow but is at least 1.5.

industrial applications or buildings, there is not yet a sufficient database from fire tests and real events.

The latest technology using CFD simulations, depending on the code used and the model assumptions, is only suitable for a limited interpolation or extrapolation of test data for FFFS in tunnels.

Over the last few years various fire scenarios have been set up to establish empirical tests for the effectiveness of FFFS in tunnels. The choice of a fire scenario needs to be made with great care and using reproducible data and risk analyses, as these have significant effects on the technical configuration, dimensioning and therefore cost of the overall safety system.

In particular when comparing the various types of configuration of a tunnel safety system, it is important to start from the same specifications.

As is generally the case with real fire tests, the choice of fire scenario must ensure that fire loads and fire scenarios are reproducible. This is why the use of standard fire loads, such as pallets, are better than real vehicles. However, a scientific deduction of the scenarios based on a risk analysis for the tunnel in question or tunnel category should be carried out.

Solid fires

In general wooden pallets are used. The dimensions correspond to the load volume of a truck. A typical fire load has the following parameters:

Length:	10.0 m
Width:	2.40 m
Load height:	2.50 m
Number of pallets:	~ 408 pieces[25]
Energy content	
(with europallets):	~ 155 GJ

As the Runehamar fire tests have shown [ING 2001] pallets, compared to a typical truck load, represent an adverse case and therefore an additional safety factor in the assessment of the efficiency of an FFFS. A cover of the entire fire load e.g. with a truck tarpaulin is recommended. Since the vast majority of fires are caused by small technical issues, a small ignition source is recommended, e.g. a 20 kW pool fire.

[25] For the simulation of the truck chassis aditionally about 250 wooden pallets were used. These are normally not involved in the fire.

Fig.34: Typical truck fire load with chassis

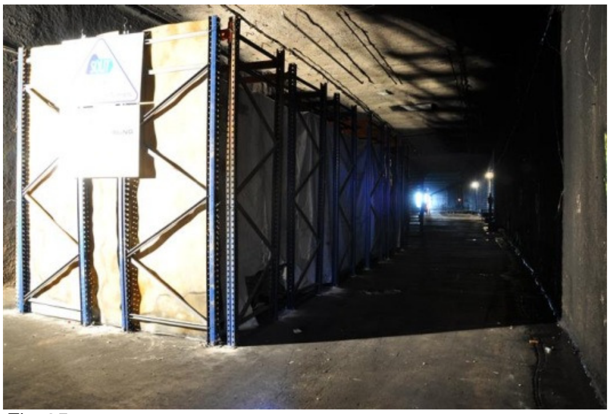


Fig. 35: Typical fire load without chassis to give a larger distance between the fire load and the tunnel roof

Depending on the configuration of the fire load a replica truck such as the one described here has a potential HRR of 100-200 MW. Because the fire progression is slower than in liquid fires, solid fires offer better evidence for a potential instead of an actual fire progression, which is then limited by the FFFS. This comes from the fact that the FFFS is activated before the maximum HRR is reached and therefore limits the maximum actual HRR.

Liquid fires

A further important fire scenario to test the effectiveness of a FFFS is a liquid fire, designed to represent a pool fire. In order to reproduce such a fire incident in a test environment, pan fires tend to be carried out instead of pool fires. This means that in the tests the fire can burn for much longer than would be expected in practice. This means that the evaluation of an FFFS with regard to its suitability to reduce the repercussions / effects of a liquid fire (formation of combustion gases, temperatures etc.) is “on the safe side”.

In order to enable a realistic evaluation of the effectiveness of an FFFS, the fire scenarios here must be based on a risk analysis to determine their size and probability. The following aspects need to be taken into consideration:

- A typical truck has 2 fuel tanks, each with a capacity of approx. 400 – 1,000 l. [SCA 2012]. It is unlikely that both tanks will release their maximum volume at the same time, e.g. by being ruptured. This means that only a limited quantity of diesel from a truck fuel tank will be present.
- The categorisation of road tunnels is regulated by special risk analyses in accordance with ADR[26]. Scenarios in which large quantities of hazardous materials are released are generally not able to be controlled by technical safety measures. In this sense, it is important to distinguish between the release caused by primary events (collision with rupture of a tank) or secondary events (a vehicle fire caused by a technical defect which extends to the hazardous substance).

Escaping liquids are led away from the tunnel by the road camber, which means that only a limited amount of liquid can accumulate on the road surface. A large distribution of liquid on the surface is therefore rather unrealistic. Furthermore, due to the thin fuel layer, the liquid burns away very quickly.

However, it is sensible to test the effectiveness of an FFFS using liquid fires. Due to the factors listed above, a fire size of up to 50-100 MW is normally used to test the suitability of the FFFS.

Basic procedure

A key factor in the mode of operation and its testing is the point of activation of the FFFS. According to RABT and similar regulations normal fire detection of a 5 MW open liquid fire, using for example linear heat detection, occurs within 1 minute. Even if in reality light scattering detectors are used for a very rapid pre-alarm, in the case of a truck fire scenario the fire detection time must be calculated.

With a liquid fire a pre-burn time of 1 minute can be assumed. However, it should be noted that the fire may not have reached its maximum HRR at this point.

The duration of the fire test must be at least as long as the time it takes the fire services to intervene. It should be based on realistic, local conditions, and in all cases at least 30 minutes.

[26] European agreement on the road transport of hazardous materials

A detailed description of the implementation of fire tests and the recommended measurement and documentation can be found in Annex 7.

2.6 Basic principles for the compensation of safety systems.

Every safety system has the task, either alone or combined with other systems, of achieving protection target, such as enabling self-rescue to take place or protecting the structure.

Regulations, e.g. RABT, prescribe tangible technical measures designed to achieve a specific safety level at the time of examination and for the individual tunnels. In general such normative approaches are based on accepted technical rules that have been tried and tested in practice.
In certain cases the measures taken from the regulations cannot be fully implemented due to external conditions[27] or a necessary raising of the safety level[28] can only be achieved without conforming to the regulations, or at least not without disproportionately high additional cost and effort.

In these cases, as in other areas of technology, (e.g. rail transport safety) deviations from normative rules are permitted when well-grounded evidence of equal safety can be produced.

Therefore in such cases alternative solutions must be found to balance the deficit and achieve at least the same level of safety. This substitution of a necessary prescribed measure by another measure is known as a compensation or “trade-off”. [THE 2012]

The aim of a compensation for a necessary measure may be the following:

- increasing the safety level for the same cost, or
- maintaining the required safety level and yet reducing the overall cost.

For some years, advances in the methods used and the introduction of increasingly complex specifications have led to a so-called "protection target-oriented approach" in the design process of safety systems. Starting from a pre-defined safety level, protection objectives can be achieved not only by measures described in the regulations, but also through a suitable combination of other measures,

[27] This may be as a result of geometric, geological, structural, economic or other external conditions.

[28] Based on a safety evaluation, e.g. through changes to the regulations or special requirements

provided that an equal or higher safety level is achieved (cf. Fig.).

When substituting measures by new measures or a combination of measures that represent the latest technology it is necessary to provide evidence that they give the same level of safety. A description of the procedure can be found in Section 3.3.

2.7 Safety evaluation methods

Safety evaluations or risk analyses can be carried out using a wide variety of different methods. These range from panels of experts running a qualitative assessment of a tunnel through other qualitative and semi-quantitative procedures to fully quantitative procedures. All of these are used in practice, according to different EU member's states and process stages.

For many issues, due to complex practical correlations regarding the calculation of reliable results, quantitative procedures have been used. These require a methodology that allows the risks to be quantified. The following three basic questions need to be answered:

- What could happen?
- How often might it happen?
- What would the repercussions be?

The answers to these questions are provided by quantitative risk analyses, which then make it necessary to carry out certain workflows.

1. Process modelling
2. Calculation of frequency
3. Calculation of damages
4. Calculation of risk
5. Calculation of risk

The individual workflows are described in brief below:

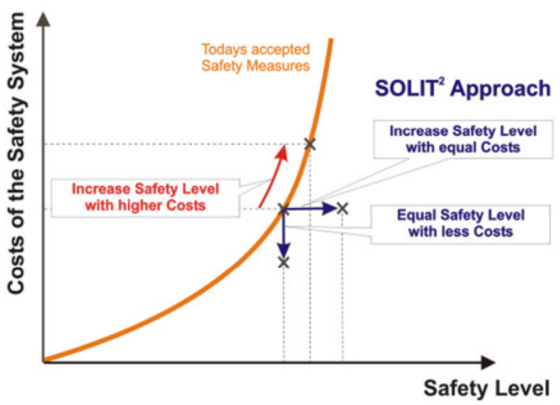


Fig. 36: Compensation - costs for safety measures and safety levels [KRA 2008]

Process modelling

Based on a triggering event (initial event, top event) event processes can be generated using event trees. The basic feature of these event processes is the transparent representation of all possible interim situations through to the final outcome. Initial events could be, for example, an accident leading to the discharge of flammable liquids or the ignition of a fire through a technical defect.

Calculation of frequency

The frequency with which the final outcome can be expected to happen is calculated using the following correlation:

$$H_{e,i} = H_0 \cdot \prod P_i$$

$H_{e,i}$:	*Frequency of final outcomes*
H_0:	*Occurrence probability of the initial event*
P_i:	*Branch probabilities P in branch i*

This calculation requires the frequency of the triggering event and the branch probabilities of the individual system responses. These are determined e.g. for the initial event by empirical values and for the branch probabilities using basic statistical principles, generic methods (e.g. fault trees) or assumptions.

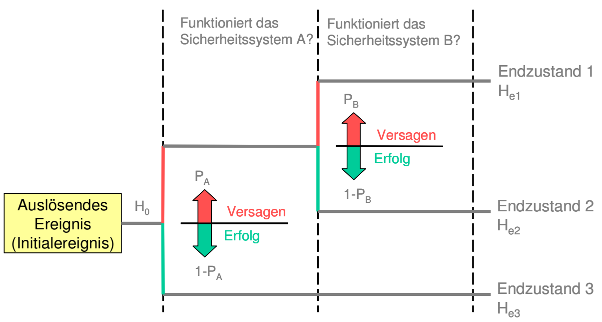


Fig. 37
Example of an event tree

Calculation of damages

The calculation of damages normally requires the use of dispersion and effect models or experience data from real tests and events. Depending on the degree of detail required various models are actually used in practice. Alongside comparatively simple aids (e.g. estimates using nomograms) complex mathematical models with higher spatial and time resolutions are also used. So, for example, CFD models can be used to estimate the effects of a free combustion using the parameters of temperature, radiant heat, flow rate and gas concentrations in both space and time. Here, however, it must be noted that CFD simulations must be calibrated with the corresponding data from real fire tests in order to achieve realistic results.

By overlaying the data with the established parameters for the corresponding protection targets (cf. Section 2.2) conclusions can be drawn about the relevant damages. In the case of enabling self-rescue to take place, this could be, for example, evacuation and escape models with exposure-related fatalities.

$$R = \sum_{i=1}^{m} (H_{ei} \cdot A_{ei})$$

m: *Number of final outcomes in the event tree*
$H_{e,i}$: *Frequency of final outcomes*
$A_{e,i}$: *Scale of damage for relevant final outcome*

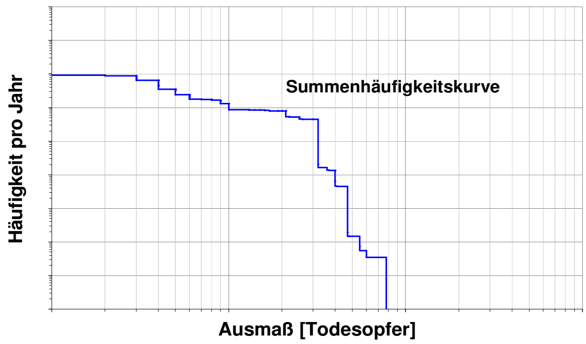


Fig.38:
Total frequency chart with the example of fatalities

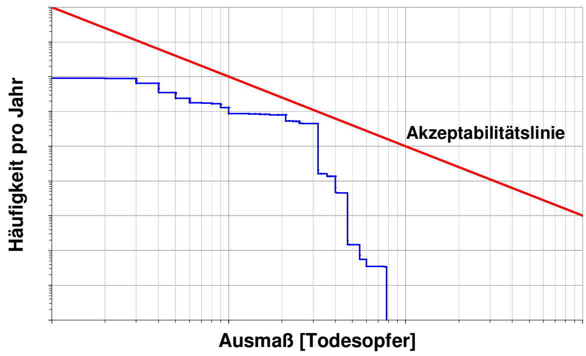


Fig.39:
Risk acceptance curve as a safety criterion for industrial systems in the Netherlands

If safety measures are taken, the scale of the damages caused by an incident also changes. If, for example, an FFFS is installed, the scale of the damages caused by a fire can be recalculated using the data from fire tests and, where applicable, interpolations or extrapolations made using CFD simulations.

Calculation of risk

As a measure for the risk potential, it is possible to use the risk that arises from the combination of the occurrence probability of the final outcome with the relevant scale of the damage.

The quantitative representation of risk can be presented as a point value (expected value for the collective risk) or a total frequency chart (see Fig.). The expected damage value corresponds to the area under the total frequency curve.

Evaluation of risk

The evaluation of risks requires the definition of a residual risk as a standard of comparison. This could either be relative comparative studies with other alternative designs for a tunnel safety system or established risk acceptance lines (cf. Example in Fig.).

For a relative comparison the risk acceptance line must be replaced by a total frequency curve from another design alternative e.g. using an FFFS, and then evaluated.

2.8 Basic principles for the calculation of life cycle costs (LCC) for tunnel construction

Tunnels are not mass produced objects, but individual constructions that are governed by the specifications of the building contractor and the environment, including geological and infrastructure-related conditions. The unique features of each tunnel construction means that it is not possible to define a structural prototype; at best individual determining factors can be assessed, such as determining the load-bearing capacity of the terrain by means of pile load tests or variations in the ground water. The building contractor and his technical advisers are therefore responsible for detailing the design of the structure and all the relevant specifications by means of descriptions and drawings. Bearing in mind the economic factors, the building contractor must then, by calling in further specialist planners where necessary, calculate the best step-by-step implementation strategy and work out a detailed plan. The life cycle of such a structure is usually assumed to be no less than 100 years. For Germany, for example, in the framework of the Regulation for the calculation of payment amounts according to the railway crossing law (Eisenbahnkreuzungsgesetz), the Federal Road Act and the Federal Waterways Act (repayment amounts computation Regulation - ABBV), each concept of use (rail/road) and type of construction (open/closed) is dealt with in completely different ways.

The increasing safety requirements for tunnel users means an increased need for operating technology. At the same time, the operating technology required for so-called normal operation is becoming increasingly complex. Specific individual components such as lighting and ventilation systems, doorways, structural coatings or electronic measuring and control systems are allocated a separate life cycle, which may be significantly different from the very long service life expected from the structural fabric (concrete, steel, masonry). Alongside rotational maintenance and commissioning work, comprehensive renovation work may be required at intervals of several decades. In the course of such work decisions can be made about whether individual components can be used again or whether entire groups of components need to be replaced by new products. This means that the life cycle of an individual product also carries the risk that necessary structural elements are no longer available on the market or the guaranteed period for the purchase of spare parts has run out. As a result of the computer-assisted operating technology consideration must be given to the fact that the compatibility of the latest generation components and technologies installed in the structure is no longer guaranteed and it may be that the entire system will need to be changed.

In Fig. a fictional project is presented. From this illustration it can be seen that there is a difference between the calculation of the life cycle costs of

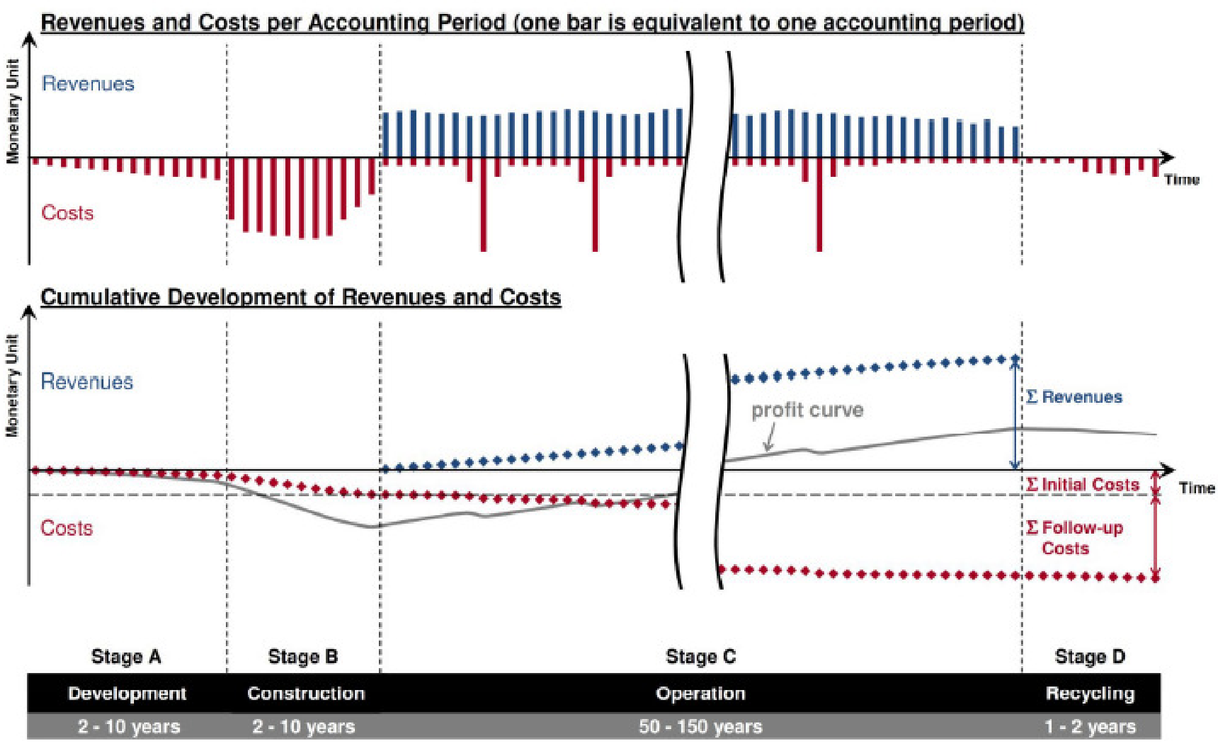


Fig. 40
The structure and its life cycle, expressed using costs and revenues

tunnel structures in Phases A - D (development, construction, management, reutilisation). Phase C ("Management") must be seen against a background which, compared to other phases, represents a very long time period – in the order of a century.

The above diagram shows the costs per calculation period - for example within a quarter or a year for energy or more seldom for renovation expenses - in a qualitative format. The revenues per calculation period reflect the income that may be generated (this only applies to traffic infrastructures in privately operated tunnels). The revenues can, however, under certain circumstances, also be expressed in the form of overall economic revenues, for example through cutting travel times. The diagram below shows the cumulative curves for costs and revenues across the entire life cycle of the structure; the difference between the two cumulative curves is shown in grey as the earning performance. Once the end of the life cycle has been reached then, as is also shown in the diagram below, the life cycle costs can be viewed directly as a sum total of the investment and maintenance costs. This methodology can also be applied to different design alternatives.

2.8.1 Systematics

Initially all cost drivers need to be identified according to date of accrual and amount. For the cost driver of "lighting", for example, there are many repeat costs for the renewal of the lighting system, the provision of replacement bulbs and the constant cost of the energy required to operate the lighting. These costs can reasonably be divided across the planned management period of the structure. Ideally, existing experience values can be used but it is more likely that the service life of technical parts and energy costs will have to be estimated. Ultimately the total economic development of a structure must be described in advance, to include every cost driver for each phase along with the relevant costs. This naturally also needs to be applied to other safety features, such as fire ventilation, passive fire protection measures or the installation of an FFFS. The sum of all costs, namely the sum of investment and maintenance costs across the entire period of time of the structure, is known as the life cycle costs[29].

2.8.1.1 Development of a life cycle approach for tunnel construction projects

In terms of public perception the costs for large, publicly financed tunnel projects are usually only linked to the one-off investment costs. But for the building contractor or operator, the costs that will be incurred during the long-term management of the tunnel structure are equally important. If the construction and operation of a tunnel is based on the principles of a life cycle model, then some key questions related to the future, as shown in the following figure, must be answered by the people responsible for the project.

When estimating the total economic cost of a specific process both the direct costs - in other words the life cycle costs - and also other economic factors need to be examined: For a road tunnel project this could be, for example, the overall economic costs arising out of shorter driving times or the optimisation of the flow of goods. However, the effects on the direct environment must also be taken into consideration, and these could include risks for the environment, local inhabitants and users of the tunnel. These are the so-called indirect costs.

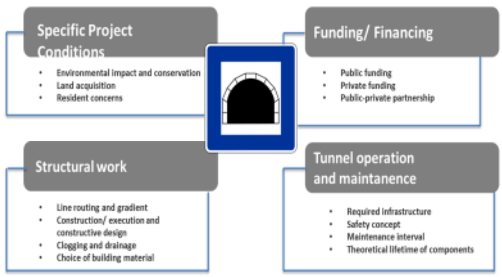


Fig. 41
Aspects to be taken into consideration when designing a tunnel

Another factor to consider is the impact that the availability of the tunnel will have on the immediate surroundings and the corresponding economic ratio, above all if the structure has to remain closed for a lengthy period of time as a result of an accident causing structural damage. The duration and scope of the hindrance or closure, which will normally depend on the scale of the damage, is very important in this instance.

[29] Also known as "whole life costs".

2.8.1.2 Description of efficiency benefits according to the relevant project phase

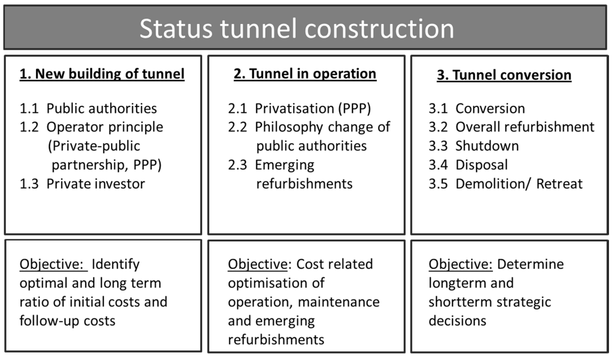


Fig. 42
Status of a tunnel structure and aim of the life cycle cost analysis

If, as part of a general renovation project, a tunnel needs to be fitted with a new inner shell, once the construction and fitting-out work has been done in compliance with the current regulations, the tunnel can be deemed to be equivalent to a new tunnel. Tunnelling and land purchase costs, which form a considerable percentage of the cost of building a new tunnel, are no longer relevant in this situation.

The long lifespan of tunnel structures and the related, aforementioned potential for fundamentally modernising tunnels as part of a general renovation project make it clear that the life cycle cost approach is a tool that can be used for more than just the initial tunnel planning. Depending on what phase a tunnel project is in, the following opportunities exist for making a life cycle assessment.

Planning a new tunnel

It is the job of the design engineer to calculate the optimum technical design of the construction from an economic point of view. Here it is not just a question of selecting the most appropriate tunnel construction process but also looking beyond the construction phase to the operating and rotational maintenance and renovation costs and evaluating alternative solutions. In an early design phase checks should be made to see whether operating technology can have a significant impact on the fabric of the building. This can be the case when selecting the ventilation concept or considering the integration of an FFFS. The aim here is to calculate the optimum investment and maintenance costs.

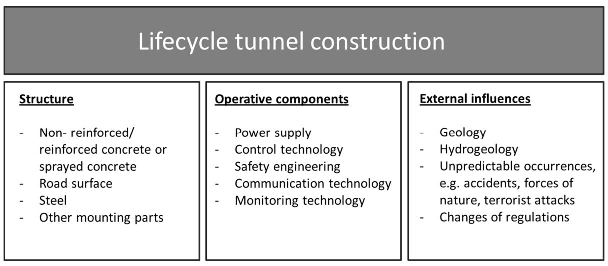


Fig. 43
Factors that affect the life cycle of a tunnel

Existing tunnel in operation

In the case of existing tunnels, the main focus is on optimising operating, maintenance and renovation costs and deciding on the right timescale for modernisation and renovation work. A key data basis is the cost history that the tunnel operator has at his disposal, which reflects a very detailed image of the expenses incurred to date for the specific structure. The potential but presumably limited framework for correcting design decisions that were made in the past by using a life cycle approach must be verified through cost-benefit analysis.

Tunnel conversion

Even in cases where a tunnel is due to be converted, it is sensible to set up a life cycle cost model. One possible scenario in this instance is the conversion of a rail tunnel to a road tunnel, as happened to the Maurice-Lemaire Tunnel in France in 1976. This 6,872 meter long tunnel had been opened in 1937. Of course, this is a very particular situation, which required in-depth, primarily economic considerations. Tunnel conversions are only occasionally required in practice.

The scenarios mentioned above show that a change of philosophy from a demand-oriented investment attitude to investment planning based on the life cycle method can occur at totally different times and is basically the result of economic considerations. The directional phases in the following table, "New tunnel construction", "Existing tunnel in operation" and "Tunnel conversion", can be seen as entry points into a life cycle cost analysis.

The life cycle of a tunnel structure is, as previously stated, determined by a multitude of factors. It is important to differentiate between factors that have already been identified in the design stages and external, not previously quantifiable and sometimes unexpected factors affecting the structure. All factors are alike in that they have a direct impact on the life cycle and therefore on the overall life cycle costs of the tunnel in question. Controllable factors include effects of the geology and hydrogeology, which represent the statistical dimensioning of the structure. Other, unpredictable events in tunnel construction include accidents, natural disasters or terrorist attacks.

Some factors, such as changes to technical standards and regulations, can lead to costs that at the time of making the life cycle cost analysis cannot be quantified or evaluated, or only to a limited extent. Changes to fiscal and interest rate policies as well as changes in the inflation rate cannot be estimated with any degree of reliability over a period of 80 to 100 years. Equally, the costs of building materials, energy and staffing may undergo price increases that are hard to predict.

2.8.1.3 Service and maintenance considerations

The service and maintenance of a building can have a significant impact on the life of individual components and the structure as a whole. This is illustrated by the following figures.

In the graph on the left at time t_1 there is damage to an item of equipment or component, which consequently leads to a significant reduction in the attainable life of the item. Proactive measures, which are taken prior to the time of the damage, can help prevent this condition and thus lead to a prolongation of the lifetime of the item. It is important to implement this within the context of the life cycle cost evaluation. The monetary difference between the required investment for the replacement of the item when time T is reached and the cost of a proactive measure is then equal to the benefits of the measure, which can only be considered in the framework of a complete analysis.

2.8.1.4 Special features of FFFS in respect of the LCC analysis

Since FFFS are highly technical installations, which must meet special requirements regarding service and maintenance, for which nevertheless at present for application in road tunnels there is only a limited amount of knowledge regarding the parameters for service life intervals of individual components, etc., detailed analysis of the maintenance procedures are required. Frequent maintenance intervals are essential to ensure high availability of the FFFS. The maintenance intervals are adjusted so that they can under no circumstances affect the availability of the tunnel, as this might result in economic consequences and financial consequences for the operator.

The following are examples of parameters which must be evaluated by means of an LCC analysis:

- Customizing the preventive measures for the FFFS to on-site tunnel maintenance intervals (for example based on DIN 1076 in conjunction with the RI-EBW-TEST, in the case of a road tunnel)
- Probability of failure of FFFS components
- Duration of the necessary preventive measures
- Maintainability of FFFS components
- Required training level of maintenance tasks
- Accessibility of FFFS components
- Costs of replacement parts
- Replacement intervals

2.8.2 Methods for calculating LCC

Various mathematical models and approaches are available, according to different countries, to help with the calculation of life cycle costs given the external conditions described above. Germany, for example, is subject to the constraints of the so-called ABBV (Directive for the Calculation of Redemption Amounts), issued by the Federal Ministry for Transport, Building and Urban Affairs (BMVBS). Alternatively, the usual mathematical processes (such as present value methods, annuity methods) and complete investment cost calculations can also be carried out, although these are significantly more complex, which are however recommended in view of the threat of implementing incongruencies. Specifically for road tunnels the PIARC requirements should be taken into account. In this

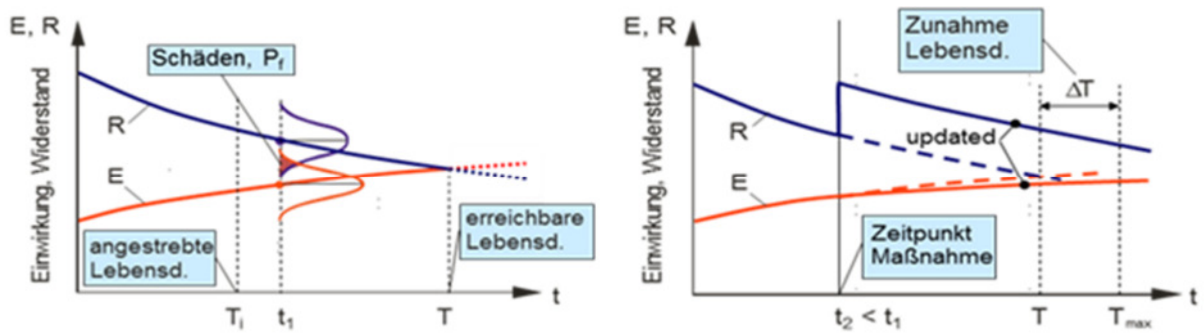


Fig. 44: Ratio of resistance and exposure according to proactive loss prevention measures

respect, the following reports are considered as central:

- AIPCR.06.08.B-2004: Planning and Programming of Maintenance budget
- PIARC.05.13.B-2005: Good Practice for the Operation and Maintenance of Road Tunnels
- PIARC.05.06.B-1999: Reduction of Operating Costs of Road Tunnels
- PIARC 2008R15: Urban road tunnels - Recommendations to managers and operating bodies for design, management, operation and maintenance

In addition, consideration of the following international standards is recommended:

- ISO 15686: Buildings and constructed assets - Service life planning
- IEC 60706: Maintainability of equipment
- IEC 61709: Electronic components - Reliability - Reference conditions for failure rates
- and stress models for conversion
- IEC 61508: Functional Safety
- EN 60300-3-3: Dependability management - Part 3-3: Application guide - Life cycle costing
- EN 13306: Maintenance terminology
- DIN 31051: Fundamentals of maintenance

Part 3 Methodological approach and minimum requirements for evaluating compensation options

Regardless of whether this is a new tunnel or a retrofit of an existing structure, due to the external conditions and economic situation a variety of different structural and fitting-out options need to be examined. In this case a number of requirements and protection objectives must be considered and evaluated against each other taking different scenarios into account. Fig. 4 shows a schematic process to compare different fitting-out options that may be used when considering the installation of an FFFS in tunnels, particularly as a compensation measure (cf. Section 2.6).

The basic process for the implementation of exemplary compensation measures designed to meet the requirements stated in the illustration or the protection targets is shown below. These requirements can be extended or altered to suit a specific tunnel.

3.1 Compensation potential

In principle the possibility exists of fully or partially compensating for one or several technical or structural systems or organisational measures by installing an FFFS.

The compensation of measures and their evaluation must always be carried out in the light of the protection targets that were determined for the original measures. The basic principle here is to achieve the same level of safety.

This is clarified by the following simplified example:

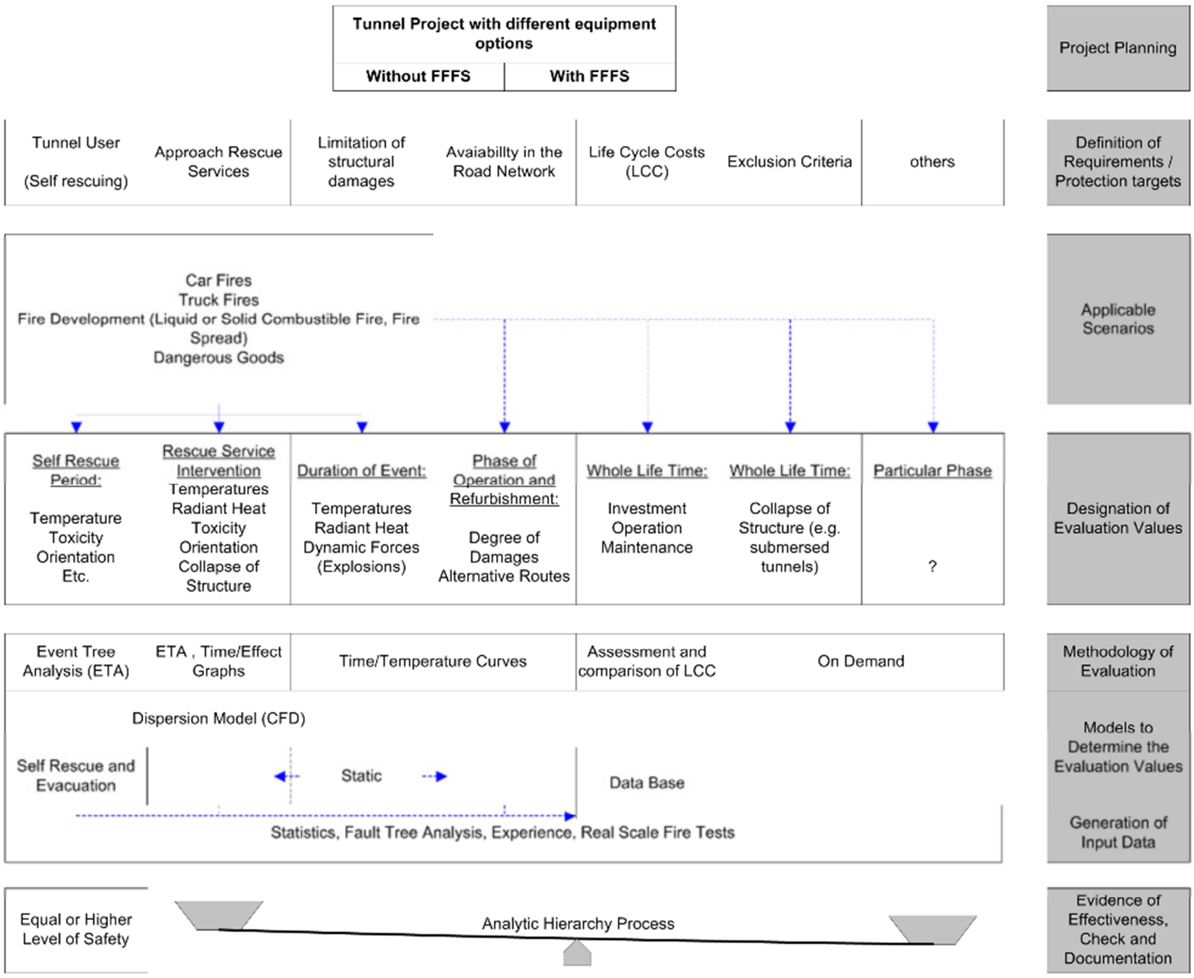


Fig. 45
Flow chart to show the compensation potential of an FFFS

Protection target:

People can effect a self-rescue from a certain part of the tunnel during a period of X minutes after the outbreak of fire (in other words, this area can maintain a survivable atmosphere for a period of at least X minutes)

Requirements:

Test fire for determining the scale of ventilation required in accordance with RABT and the risk assessment: 100 MW, structural/geometric requirements determined by the tunnel (length of tunnel etc.)

Measures according to RABT:

- The extraction of combustion gases via a false ceiling with a capacity of 300 m³/s to limit the spread and to create a minimal layer of smoke.
- Emergency exits every 300 m in safe areas
- Escape route markings, orientation lighting, loudspeaker announcements etc.

Required deviation from regulations:

- Do without the false ceiling and combustion gas extraction and instead install a longitudinal ventilation system

Compensation measures:

- Installation of an FFFS
- Emergency exits every 350 m in safe areas
- Increased escape route markings/lighting to help people to locate the emergency exits quickly even when the FFFS has been activated[30]

The decision about whether a compensation measure is reasonable must be made according to the individual situation and can be based on an evaluation of the life cycle costs (LCC) alongside evidence to show that the equivalent safety levels will be achieved, as described in Section 3.5. The evidence to prove the equivalent safety level of various alternative designs is explained in Section 3.3.

The following chapters briefly describe the basic compensation options with regard to protection targets. It must be pointed out that this is a general description. The efficiency of the various system technologies with regard to the individual protection targets can vary considerably and must be tested for individual cases. The measures given here have been taken from the results of the fire tests carried out as part of the SOLIT² research project.

Finally, the methodology for calculating a qualitative compensation potential for the area of user protection, passive protection and emergency rescue is explained.

3.1.1 Self-rescue phase

The primary measures to ensure a survivable atmosphere in the self-rescue phase are fire ventilation systems and exits to secure areas via escape routes in neighbouring tunnels or separate escape tunnels. Here the intervention of an FFFS can offer considerable compensation potential, which can also have repercussions on future construction plans.

Fire ventilation

In the case of an FFFS with a very large cooling effect, e.g. water mist systems, there is a significant reduction in the temperature of the combustion gases as well as a very considerable volume reduction. In addition, the maximum HRR is significantly limited, especially in the case of solid fires. With liquid fires the spread of the fire to neighbouring objects is hindered.

The following compensation options are available when an FFFS is installed:

- The critical flow velocity of the longitudinal ventilation, which is intended to prevent pushing back the smoke layer, can be reduced depending on the tunnel cross-section. In new tunnels either the number or the capacity of jet fans can be reduced and existing tunnels can be retrofitted with the same configuration in order to deal with larger fires.
- With the installation of a transverse or semi-transverse ventilation system the efficiency of the combustion gas extraction process can be increased. This means that in new tunnels the capacity of the smoke extraction system can be reduced or where a tunnel is retrofitted with the existing configuration larger fires can be dealt with.
- In many cases, the installation of an FFFS means that a transverse or semi-transverse ventilation system can be replaced with longitudinal ventilation. This brings considerable structural implications and savings opportunities in terms of the cross section of the tunnel

[30] It is not currently possible to produce a calculation or simulation. This is a matter of empirical experience values.

or the structures and operational fittings required for the smoke extraction system.

In fire tests[31] it can be observed that the capacity of the fire ventilation can be tripled when a water mist FFFS is used at the same time[32] .

Distance between emergency exits

Through the improved environmental conditions provided by the intervention of an FFFS during the course of a large fire an assessment can be made about whether the distance between emergency exits can be extended. This, in particular, can lead to considerable savings if it obviates the need for a separate escape tunnel.

Where an FFFS is installed to optimise conditions during the self-rescue phase, it should be designed to be activated immediately, as is the case with the fire ventilation. It is particularly important to ensure that the FFFS does not endanger the tunnel user in any way, e.g. through the risk of suffocation or slipping, or impaired visibility.

When assessing visibility the comparison should be made with the case "fire without FFFS" rather than the case "no fire in the tunnel". In order to improve orientation in the activated areas of the FFFS simple measures, such as escape route systems, can offer a significant improvement.

3.1.2 Emergency rescue phase and fire fighting

For the emergency rescue and fire fighting phase the measures described in Section 2.4.3.2 apply:

Fire ventilation

The following options apply to the compensation of the fire ventilation, as explained in Section 3.1.1. This is particularly important for the emergency rescue phase due to the long time delay following a fire incident. In accordance with RABT and other regulations, the test fire calculation for fire ventilation is 30 MW, and with increased truck capacity 50 - 100 MW. This does not reflect the maximum size of the fire that can be expected but it serves to help determine the scale of the fire ventilation for the self-rescue phase. At the point at which the emergency services intervene, however, in the case of a relevant scenario, e.g. a full truck fire, the fire is likely to be significantly larger, so that here, too, an increase in the efficiency of the fire ventilation is a real advantage. Along with the positive effects of the FFFS on the working conditions sur-surrounding the fire, it is also possible to reach the source of the fire quicker and more safely.

Intervention times and choice of location for the fire brigade

Because of the travel times (e.g. in the case of tunnels in rural areas) and the consequent availability and equipment levels of the surrounding fire brigades, some tunnels, especially those with a higher level of risk, require stationing their own fire brigade close to a portal.

The installation of an FFFS significantly reduces the risk of a fire spreading. This in turn reduces the effects of a fire in the tunnel on both people and structure, giving a much larger window of time for the emergency services to arrive and begin emergency rescue measures or start fighting the fire.

3.1.3 Structural safety

The installation of an FFFS can limit temperatures and radiant heat, shortening the length of time that structural elements are exposed to the heat. As a result, measures can be adjusted to suit the protection of the reinforcement against high temperatures and the consequent reduction in stability of the structure.

Altered fire curve calculation

Normally standard time/temperature curves are used to determine the dimensions of passive fire protection measures (cf. Section 2.2.2.2). When an FFFS is installed, it is possible to apply a different time/temperature curve. This then contains the time-dependent temperatures calculated in the context of fire tests. Such project-specific temperature curves can be used to determine the dimensions of structural elements as normal. In critical tunnels in particular (e.g. underwater tunnels) there is considerable potential for savings in this sense.

No retrofitted passive fire protection measures

In particular when retrofitting tunnel systems in accordance with new, higher specifications (modified time-temperature curve), fire protection claddings are often fitted retrospectively. However, the required regular building inspections can no longer be fully implemented. As stated in the previous section, here too the installation of an FFFS may act as compensation for such measures.

3.1.4 Other effects

In addition to the measures explained in Section 3.1.3 for the compensation of structural measures

[31] See annex 2 for further information

[32] A similar effect of the fire ventilation (longitudinal and semi-transverse) was observed for free combustion with approx. 30 MW and fires with approx. 100 MW and an activated FFFS.

it can be assumed that the damage to the structure and the operating equipment is less in the event of a fire. This means that the installation of an FFFS can have further positive effects:

- The costs for the repair work to the structure and the operating equipment following a fire are reduced.
- The necessary time for repair and renovation work is considerably reduced. This may mean a reduction in losses through the lack of toll income. Tunnels that are free of charge can also expect to see considerable benefits by reducing the non-availability of the tunnel and the subsequent economic damage.

3.2 Basic process for the implementation of compensation measures

3.2.1 Compensation for user protection (distance between escape routes, fire ventilation)

3.2.1.1 Basic principles

For the protection of road users in case of fire the self-rescue phase under the prevailing escape conditions in the critical first minutes after a fire outbreak is critical. Escape conditions are determined by a number of interacting parameters and effects. Firstly, there are influences from the fire scenario itself, characterised by the heat and smoke release. On the other hand, there are technical and structural constraints which serve the fire detection, smoke extraction, (fire ventilation) or guidance of people (emergency exits, escape route signage, loudspeaker announcements, etc.). The safety concepts at the heart of the current regulations contemplate exclusively measures for fire detection and smoke and management of people. Consequently, for a comparative safety assessment, the fire scenario itself must be considered as an "immutable" cause.

By influencing the cause of fire with an FFFS the effects described in Section 2.4.2 can be achieved. The reduction of the fire development and the cooling of the combustion gases and the consequent reduction in volume allow the compensation of the following equipment items:

- Ventilation system: Elimination of a false ceiling with smoke extraction via controllable dampers and fans, possibly with a ventilation flue, execution of a pure longitudinal ventilation system using jet fans
- Reduction of the required longitudinal ventilation rate and thus a reduction of the required fire ventilation capacity.
- Reducing the power of the smoke extraction
- Test fire capacity: Reducing the required dimensions of the largest energy release rate, thereby reducing design of fans and the associated power supply
- Emergency exit spacing: Optimization of the required spacing of emergency exits, which are costly to produce.

In addition to the above equipment, in the case of retrofitting of old tunnels several missing measures can be compensated for by the use of an FFFS.

3.2.1.2 Identification and evaluation of the potential compensation

The potential compensation in relation to the road users safety arising from the use of an FFFS requires the comparison of different variants in terms of self-rescue equipment for the tunnel under consideration. The reference is a tunnel equipped in accordance with applicable directives.

Scenarios

The definition and analysis of realistic fire scenarios, with which the particular security level is shown, is essential. These scenarios must simulate on the one hand the potential for uninterrupted fire development and, secondly, the interaction between technical equipment and fire development (e.g. FFFS). Because of the high costs of the calculation of scenarios a compromise must be found between a comprehensive account of all scenarios and for the relative comparison of permissible simplifications or reductions.

For a consideration of safety equipment used exclusively for fire detection, smoke extraction and guidance of people, the consideration of pure pool fires has been established as an unfavourable "worst case" scenario. This observation, however, considers the influence of an FFFS in the early stages of a solid fire only to a limited extent. In addition, the frequency distribution between solid fires and pool fires is not taken into account (see Section 2.5.1 . Therefore, when considering equipment which has a direct influence on the fire itself, other scenarios must be taken into account.

Evaluation magnitudes, methodology and models

The evaluation magnitudes for the analysis of user safety are all time-dependent adverse effects on people such as temperature, toxicity, orientation ability, etc. To determine the extent of damage, appropriate flow calculations using CFD models with escape and evacuation models must be combined. These are detailed in Section 2.5.1. The values obtained are inputs to the procedure quantitative risk assessment using event tree analysis described in Section 3.3.

3.2.2 Compensation for self rescue and fire fighting measures

3.2.2.1 Calculation of compensation potential

As a result of the effects described in Section 2.4.3.2 the emergency aid measures can be carried out quicker and more safely. This reduces the effects of the fire on the structure and on tunnel users.

In addition, by controlling the fire (cf. Section 2.4.2) there is also a longer period of time available for carrying out emergency aid measures.

The abovementioned effects can be considered in the light of the following factors within the framework of an emergency aid concept[33].

- Environmental conditions in the direct proximity of the fire
- Location, availability and equipment of the nearest fire brigade
- Location, equipment of the nearest specialist fire fighting unit
- Access options for the relevant tunnel portal
- Supporting measures (e.g. emergency exits, escape tunnels) that allow the fire brigade to advance
- Use of quick response emergency services for the initial measures

However, the emergency services always need to intervene in order to carry out emergency rescues and fire fighting actions.

3.2.3 Compensation of passive fire protection measures

3.2.3.1 Calculation of compensation potential

The construction measures described in Sections 2.2.2.2 and 3.1.3 with regard to the compensation potential with the installation of an FFFS are evaluated below.

Normal concrete with no additional fire protection

The potential reduction in the concrete covering gives the following compensation potential:

- The reduction of the excavation line and consequent savings that would be incurred by expanding the size of the cross-section of the tunnel
- The reduction of disassembly costs, as there would be less concrete and reinforcement involved
- In false ceilings it may be possible to do without the galvanised wire-mesh reinforcement (N94)
- The reduction of the repair costs following a fire and a shorter time out of operation

Special fire protection concrete

The installation of an FFFS could reduce or remove the fibre content as the temperature load would be lessened.

- The reduction of concrete costs through a lower fibre content
- The reduction of costs that could arise through the replacement of the fire protection measures and therefore a shorter time out of operation

The protection of the normal concrete using fire protection panels or fire protection plasters

The lower temperatures that could be expected in the event of a fire combined with the FFFS means that the thickness of the fire protection claddings or fire protection plaster could be reduced or these measures could be dispensed with altogether.

- The enlargement of the excavation line for the installation of the fire protection claddings or fire protection plaster and the consequent additional costs could be reduced
- The reduction of costs that could arise through the replacement of the fire protection measures and therefore a shorter time out of operation

If additional technical fire protection measures are required, for example in underwater tunnels, these could possibly be dispensed with or reduced in the case of new road tunnels by the installation of an FFFS. Here it is necessary to examine in individual cases whether the installation of a solution of a similar value is sufficient to safeguard the protection targets of the fire protection measures.

In particular in the case of existing tunnels where additional fire protection measures are required, the option of retrofitting an FFFS offers an alternative to the use of fire protection claddings or fire protection plaster.

3.2.3.2 Methodical implementation

The dimensions of the passive fire protection measures are normally determined by structural analysis taking into account an accepted time-temperature curve.

The installation of an FFFS means that a modified time-temperature curve can be applied, resulting from a fire test at a 1:1 ratio. Checks must be

[33] The fire and emergency aid legislation of individual regions must always be taken into account.

made to see if this new fire curve calculation requires a safety margin.

Alongside a reduction in the maximum temperature, consideration can be given to the fact that the area of the structure affected by the fire is reduced due to the fact that the fire is encapsulated in a small area directly above the source of the fire. Even just a short distance from the source of the fire critical temperatures were no longer reached on the walls and ceiling in the direction of the air flow and thus damage to the structure was averted.

3.2.4 Further compensation options and additional benefits

3.2.4.1 Minimising damage in the event of a fire

The effect of high, long-lasting temperatures on the structure in the event of a fire can lead to the spalling of the concrete and the consequent strong heating to a loss of capacity of the load-bearing reinforcements. People in the tunnel (e.g. emergency services) can also be at risk from spalling concrete. This is also to be assumed in the event that passive fire protection measures have been carried out in the tunnel, as these tend to only offer protection for a defined period of time (e.g. 90 minutes) and in any case they will need to be renewed after a fire in the areas affected by the high temperatures.

The risk of spalling increases as the rate of heating speeds up. To avoid spalling, on an unprotected concrete surface the rise in temperature should not exceed an average of 70 K/min in the first ten minutes of the fire [HAA 2008].

If the temperature rises at 200 K/min, in contrast, the first signs of spalling can appear after just 1.5 minutes [DEH 2007]. As the fire progresses the spalling becomes larger and can lead to the load-bearing reinforcement being exposed. This can have a negative impact on the load-bearing capacity of the structure. This is something that must be avoided in critical tunnels (e.g. underwater tunnels) due to the high degree of damage that would almost certainly be caused.

The installation of an FFFS can prevent higher temperatures from occurring over a longer period of time. This means that the repair costs following a fire are considerably lower, regardless of whether passive fire protection measures were in place or not. The benefits of compensatory measures to be considered against this background is in accordance with the reduction of costs through the application of the measures (FFFS).

3.2.4.2 Availability within the road network

Depending on the type of building and its location in the network infrastructure, business interruption or downtime can lead to considerable damage. In this sense, damage should not be seen as a reaction of the structure to a difference of resistance to the action, but as a financial expense which should be considered as direct or indirect. Direct costs incurred on the operator side, for example, include monetary losses, in consequence of the lack of tolls and transit fees. Indirect costs include expenses borne by the whole of society, for example in the form of extra travel time for road users, an increase of CO_2 emissions, regional effects and impacts on the economy as a result of a deterioration in economic conditions, etc.

Naturally, expenses so calculated correlate with the degree of damage suffered by the structure in case of fire: A higher loss usually leads to higher maintenance requirements on the building, which in turn is associated with increased time needed to restore the serviceability of the structure. The general rule here is that the effects of a fire are highly dependent on the specific construction and cannot be generalised. Nevertheless, they are of great concern in an overall approach, particularly with regard to the consideration of the life cycle cost of the structure. This is especially true in the case of privately operated buildings.

The benefits of compensatory measures to be considered against this background is in accordance with the reduction of costs -both direct and indirect- through the application of the measures (FFFS).

3.2.4.3 Reduction of the LCC

Even if a technical measure is replaced by an alternative measure, it may be possible under certain circumstances to reduce the overall LCC. This is especially the case if technically very complicated and maintenance-intensive systems are being replaced by alternatives.

3.3 Evidence of equivalent safety levels in different fitting-out options

3.3.1 Basic principles

Quantitative information regarding the safety level in a tunnel, carried out in accordance with the specifications of recognised regulations, is not defined in any greater detail. On the other hand, qualitative demands are made of the specified measures, which " ..lead to the fitting-out of road tunnels according to a standard set of principles and criteria and the secure operation of a quality appropriate to the relevant traffic and local conditions in due consideration of economic factors. The elements of the technical fitting-out must be designed and installed in such a way that they are robust, safe and easy to maintain .." [RAB 2006].

Any deviations from the safety specifications in accordance with European directive 2004/54/EG or RABT or any other valid regulations, must not fall short of the safety levels specified in the directives. The evidence for this must be provided using recognised methods of safety evaluation, as described in Section 2.7.

The integration of an FFFS may not contribute to any increase in residual risk and must therefore be evaluated as part of a comprehensive examination of the entire tunnel safety system.

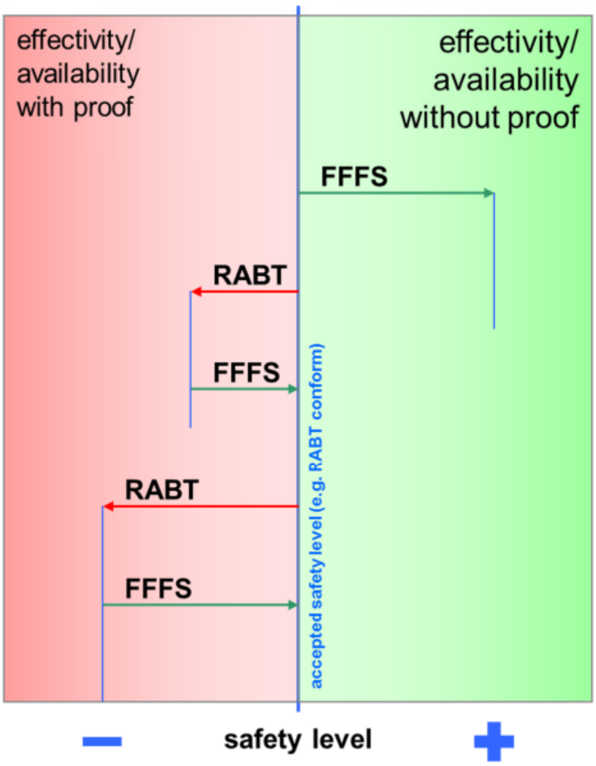


Fig. 46
Equivalent safety through various measures and compensation using the example of an FFFS

As a reference level, a road tunnel fitted out in accordance with RABT is shown below. With such a road tunnel, compliance with the safety requirements is assumed, even if some residual risk still remains. The safety level achieved by full compliance with RABT for a particular tunnel also represents a design safety level[34] and serves as a reference for any deviations in the design or fitting out of tunnels.

Since the method to be applied is however only described in its basic approach, other reference levels, such as those taken from other regulations, may also be used.

Comparison of effectiveness

If the safety features or equipment of a tunnel do not comply with RABT specifications there is an increase in the initial risk. This increased risk must be balanced out by compensatory measures. As described previously, the implementation of an FFFS can provide this compensation.

Fig. *4* shows the main connections between the comparable safety level (blue line) and the decrease in safety levels caused by the deviation from RABT specifications[35] (red arrow) as well as the effectiveness of an FFFS in addition to the required safety level (green arrow). The FFFS can be seen either as a compensation measure for deviations or serve as an additional measure in the sense of over-compliance with the requirements.

If the FFFS is implemented as an addition to a tunnel that complies with all the regulations then its effectiveness and availability with regard to the achievement of specified protection targets does not need to be demonstrated.

3.3.2 Safety evaluation of different fitting-out options

The safety evaluation requires processes and methods that show the effects of individual measures, such as fire ventilation or an FFFS, which can be used to achieve the safety level. Quantitative risk analysis allows for a detailed examination of a wide variety of determining factors to be carried out. The methodology required is described, for example, in the "Evaluation of the safety of road tunnels" [BAS 2009]. The risk that arises from the combination of the occurrence probability with the relevant damages that could arise serves as the measure for the level of safety.

$$R = \sum_{i=1}^{n} H_{ei} \cdot A_{ei}$$

H_{ei}: Frequency of final outcome I
A_{ei}: Scale of the damage in the final outcome

Where applicable, modified values from compensation measures can be used to calculate the extent of the damage.

[34] In other cases it is possible to talk of risk acceptance values and risk acceptance limits

[35] Represents the increase in residual risk

3.3.3 *Calculation of occurrence probability*

The calculation of occurrence probabilities for the final outcomes is done using event trees, in which starting from an initial event the effectiveness of specific safety functions is requested until the final outcome has been reached and the results combined in a logical model. Every question that requires a system response involves making a decision about the probability of success or failure. This creates a network of different branches in the event process leading to the final outcome. The scale of the damage can then be calculated for each individual event process. A summation of the contributing risk factors (frequency x scale of damage) for the individual branches then gives the overall risk associated with the initial event. The conventional layout of an event tree is shown schematically in Fig. *47*.

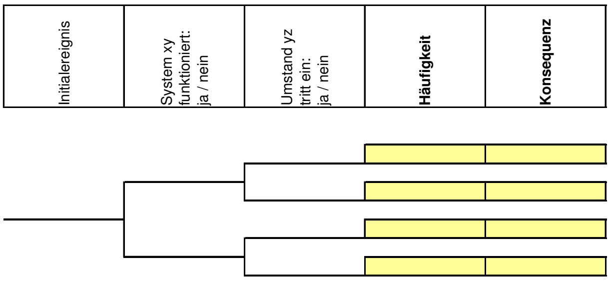


Fig. 47
Example of an event tree

When creating an event tree the events must be presented in chronological order. Here only those system responses are shown that have a direct effect on the chain of events. The availability of the indirectly used subsystems, such as the power supply, is not considered to be part of the chain of events but instead is assumed to be implicit in the corresponding branch probabilities.

The frequency of the final outcomes is then shown by linking the occurrence probability of the initial event with the branch probabilities that arise in the course of the event process and is calculated as follows.

This calculation is only possible when the occurrence probability of the initial event and the branch probabilities of the individual system responses are

$$H_{ei} = H_0 \prod P_i$$

H_{ei}: *Occurrence probability of the final outcome i*
H_0: *Occurrence probability of the initial event*
P_i: *Branch probabilities in the course of events*

known. The following branch points can occur in the course of events:

The corresponding branch probabilities are either known through statistics, calculated by expert consultations, or have to be determined through fault-tree analysis.

Branches	***Branch specifications***
Fire progression according to vehicle type	Truck 5 MW / Truck 30 MW / Truck 100 MW
Time period	Day / Night
Traffic situation	Flowing / Congestion
Detection successful	Yes / No
Tunnel closure successful	Yes / No
Road users alerted	Yes / No
Fire ventilation activated	Yes / No
FFS activated	Yes / No
Greater magnitude	Yes / No
Emergency rescue / Fire fighting	Yes / No

Fig. 48
Examples of branches in the course of events

The fault tree analysis is a so-called top down method which starts from a top event (branching point) and describes the undesirable event through the logical connection of sub-events, which constitute the causes of the top event. The sub-events are in turn traced back through logical connections to further sub-events until the base event has been reached.

At the base event level the events no longer have any functional dependence. The fault tree analysis therefore traces the defined undesirable event through logical connections back to the base event, whose occurrence probability is either known or can be estimated.

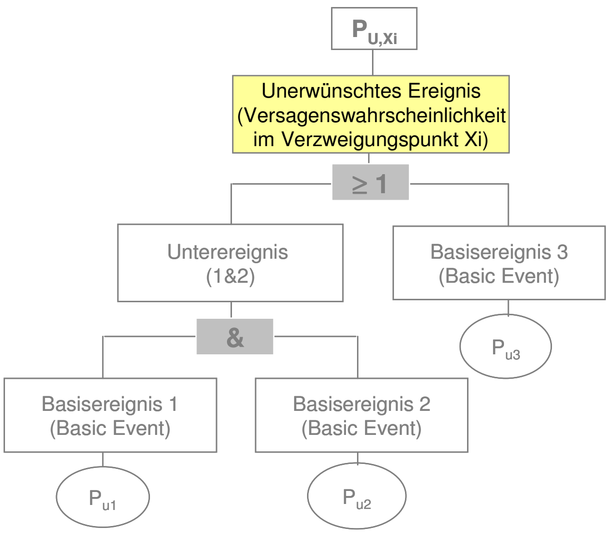


Fig. 49:
Example of a fault tree

Fig. 49: shows an example of the flow of a fault tree consisting of three base events.

The logical interactions between the sub-events are examined using logical AND/OR gates. The undesirable event in this example occurred when the sub-event (1 & 2) or the base event 3 occurred (OR gate). In order for sub-events (1 & 2) to occur, the base events 1 and 2 had to occur at the same time (AND gate).

From the lowest level, which shows the base events, each connection is calculated in succession until the undesirable event is reached.

The probability of the non-availability of a safety system is the equivalent of an undesirable event P_u, where P_{ui} is the non-availability of an individual system component.

In order for an event to occur from an AND gate all sub-conditions i must occur. This is, for example, important when representing redundant safety systems, where all subsystems have to fail.

AND – gate: $$P_u = \prod_{i=1}^{n} P_{u,i}$$

An event or OR gate occurs when at least one of the sub-conditions i occurs. In the case of systems that have multiple causes for a failure, this logical gate system can prove useful.

OR connection: $$P_u = 1 - \prod_{i=1}^{n} \left(1 - P_{u,i}\right)$$

3.3.4 Calculation of the scale of damage

The calculation of the scale of the damage requires on the one hand the determination of the scale of the impact and on the other hand the repercussions resulting from this for the users and the structure. Both magnitudes are to a large extent dependent on the initial event.

The use of data from fire tests

The best way to demonstrate the effects of fires, in particular when an FFFS has been activated, is naturally to use the results of fire tests. Where these are calculated in a suitable way (cf. section 0), these should be applied.

The use of CFD modelling

Where the starting parameters and the mathematical models of CFD simulations are validated by data from real fire tests these can be used to adjust test data to suit real tunnel constructions or changes in environmental conditions. The effects of a fire can then also be calculated without the need to run fire tests for every individual tunnel.

Furthermore, CFD simulations can be used given the above specifications to demonstrate the scale of the impact on, for example, users and structure with greater precision than can be achieved through the technical measurements collated in fire tests. However, it must always be borne in mind that a simulation provides no more than an exemplary illustration, with limited precision. The quality of the input data and the mathematical models used are of critical importance.

Fig. 50 shows an example of the temperature effects calculated using a CFD code following a 30 MW fire in a one-way traffic tunnel with free flowing traffic.

To determine the impact on the users a number of overlapping effects must be taken into account. Alongside the external effects (e.g. temperature or gas concentration) on the human body caused by

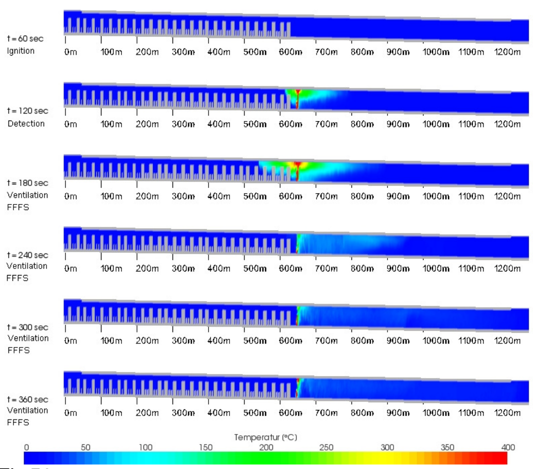


Fig.50:
Temperature effects following a 30 MW fire in a one-way traffic tunnel with free flowing traffic with FFFS

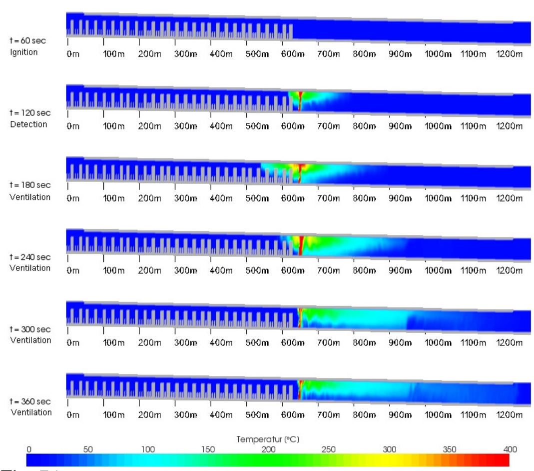


Fig. 51:
Temperature effects following a 30 MW fire in a one-way traffic tunnel with free flowing traffic without any FFFS

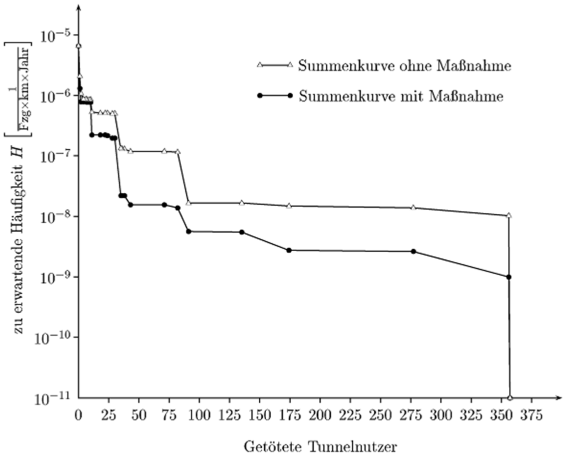


Fig.52:
Example of a H-A diagram to estimate the effectiveness of measures according to tunnel user fatalities.

external influences such as temperature or concentrations of gas, the entire scale of the damage also includes the number of people that may be affected in the area in question. Both are highly dynamic procedures between which there are contradictory dependencies due to changing external conditions. The effects arising through pressure, smoke and temperature are also dependent on the activation and effectiveness of technical equipment. The number of people affected is in turn dependent on the traffic situation, the time of detection of an event and the possible closure of the tunnel as well as the escape conditions present in the tunnel.

A similar situation applies to the effects on the structure. Here it is necessary to consider the temperature and radiant heat levels as well as the duration of the effect on a specific area. For example, these can be very different in situations with or without an FFFS.

3.3.5 Calculation of risk

To demonstrate the risks, event trees are used to calculate the frequency of the final outcomes and the relevant corresponding scale of damage according to the size of the damage and shown in H-A diagrams as total frequencies. This allows the calculated risks to be show in comparative form. Fig., for example, shows the progression of risks in the form of tunnel user fatalities according to the measures in place. However, this can also be used to show other risks, e.g. structural damage.

3.3.6 Evaluation of risk

In the absence of any pre-defined acceptance threshold, the risks can only be calculated using relative comparisons. A tunnel fitted out in line with RABT specifications usually serves here as a standard of comparison. A measure is considered to improve safety if it can be used to reduce risk.

3.4 Simulation models for use in verification procedures

Complex interactions exist between tunnel users, the structure and safety systems and installations. The geometry of the tunnel (cross section, gradient) affects the spread of smoke and temperature. The spread of smoke and temperature is affected by a ventilation system or FFFS. However, these also have an effect on the users, the structure and the effectiveness of other safety features (lighting, escape route markings, emergency exits etc.). In order to take these interactions into account when quantifying the extent of the damage and calculating the effectiveness of the measures, high resolution space and time-related mathematical models are used to show

- flow and dispersion simulation,
- escape and evacuation simulation,
- Traffic flow simulation.

The requirements of the relevant simulation model are described in brief below.

3.4.1 Flow and dispersion models

Space and time-related information about pressure, speed, temperature and concentration distributions are essential to enable detailed calculations of the main effects to be made. A representation of visibility is only possible to a very limited degree due to the complexity of human sight.

In addition, procedures of energy and heat transfer as well as several phases (solid, liquid, gaseous) and chemical reactions must be able to be shown.

The basis for the description of these magnitudes and processes is given by the continuously formulated, time-dependent differential equations for the conservation of mass, the conservation of momentum, the conservation of energy and the conservation of material, which can only be solved using numerical processes due to their complexity.

The realistic depiction of the flow and dispersion processes require the solution of equations

- for a non-stationary situation,
- in a 3-dimensional space
- for compressible flows.

Further, multi-component and multi-phase flows (liquid, gaseous) must be depicted and further sub models used to calculate

- turbulences (LES, kε model),
- fires (solid fires, liquid fires, gas fires)
- heat transfer
- phase transitions and
- chemical reactions.

With the help of the models additional optional ventilation conditions must be able to be shown using fans and meteorological influences as well as the effects of the FFFS.

As a result of the numerical calculations continuous information must be provided regarding:

- energy release
- temperatures and radiant heat
- flow rates and dispersion
- Gas concentrations.

Regardless of the type of simulation model used it is essential for the mathematical results to be validated by means of a real fire test and for this to be carried out for scenarios with and without the activation of an FFFS. To this end Section 2.5.4 shows some scenarios in a test tunnel. Only when the input parameters and mathematical models show sufficient agreement between the fire test in the test tunnel and the simulation can these be used for interpolations and extrapolations as well as for other estimates of the effects of the ventilation systems, FFFS and other safety systems that could affect the fire.

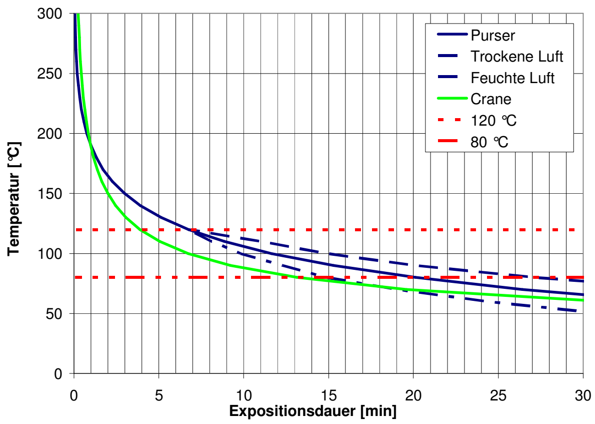


Fig. 53:
Mortalities as a result of high temperatures [BAS 2009]

In particular with the use of the input data of the FFFS it must be noted that the results of the simulation are only applicable to the type used in that particular fire test.

3.4.2 Escape and evacuation models

Models designed to calculate escape and evacuation serve, together with various other safety features, such as fire ventilation, emergency exits,

$$Dosis = \int_{t_0}^{t_{ende}} C^n \, dt$$

C: Concentration [ppm]
t: Exposure time [s]

Calculation of probit variable Y:

Y = k1 + k2 ln(dose)

Y99 = 8
Y50 = 5

FFFS, guidance systems, communication systems etc. and taking into account the effects on the human body, to deduce self-rescue areas or the scale of damages to individual people.

3.4.2.1 Impact models

With the help of impact models, human mortality can be calculated according to the scale of effects such as air pressure, temperature, radiant heat and any concentrations of harmful substances[36] .

Effect of high temperatures

The energy released following a fire can have a damaging effect on people through radiant heat or as a result of convective heat transfer. The effects of radiant heat tend to be restricted to the area in the direct proximity of the fire[37], while convective heat transfer can be carried with the air flow to more distant areas, up to several hundred metres away. The corresponding increase in the ambient temperature can, depending on the period of exposure, lead to burns or the build up of heat in the human body. Fig. 5 shows the expected mortality as a result of high temperatures (convective element). The key issue here is that the temperature and the period of exposure both play an important role.

In order to evaluate the effect of high temperatures on the emergency services the radiant heat must also be taken into consideration. Here, too, the height of the temperature and the duration of exposure must be considered.

[36] Mortality: Deadliness of a toxin

[37] Here a distance of a few metres in the case of a large fire up to 100 m can be assumed.

Influence of toxic and suffocating elements of combustion gases

Among the many toxic components of combustion gases that are released in combustion gases, the main toxic effects on humans are basically caused by carbon monoxide (CO) and prussic acid (HCN). Both gases have a narcotic effect, even in low concentrations, and can lead to death very quickly in the case of long exposure periods or high concentrations.

Probit functions can be used to determine mortalities caused by combustion gases[38]. With the help of the integrals for the dose and the probit variable Y the limit concentrations can be determined depending on the time of exposure and the consequent mortalities.

To calculate the probit variables the constants shown in Fig. can be used. More details can be found in specialist literature.

These formulas can be used to create limit curves for mortality rates following exposure to CO or HCN.

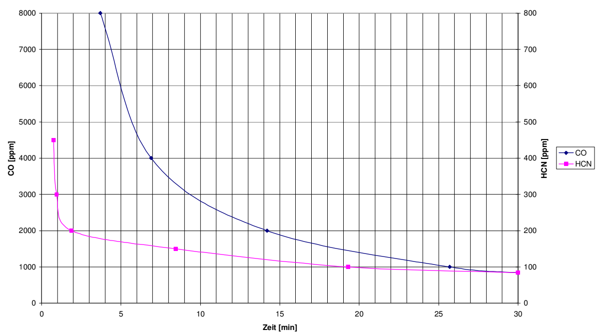


Fig. 54
Mortality rates following exposure to CO or HCN [BAS 2009]

Reduced visibility due to smoke

The ability to carry out a successful self-rescue is heavily influenced by orientation ability. In tests it was demonstrated that [BAS 2009] the speed of

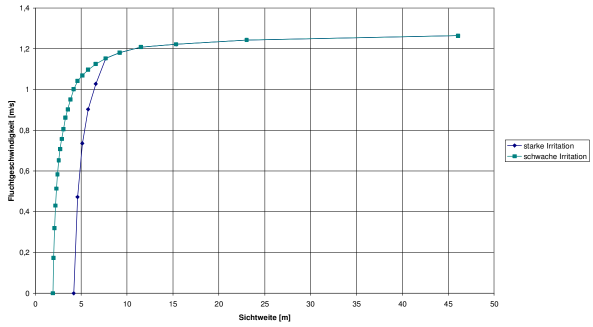


Fig. 55:
Correlation between visibility and speed of escape for reflecting objects [BAS 2009]

escape is directly dependent on the existing visibility. As shown in Fig, a visibility of 10 m or less leads to a drastic reduction in the speed of escape. From approx. 5 m visibility purposeful forward progress is no longer possible. It should be noted that these tests were only carried out for the case of a free combustion.

Description of substances	***K1***	***K2***	***N***
Carbon monoxide (CO)	-37.98	3.70	1.00
Prussic acid (HCN)	-9.80	1.00	2.40

Fig. 56:
Sample probit constants

When an FFFS is used the orientation ability becomes even more relevant. In tests with experiments as part of the SOLIT² project it became clear that orientation in the activated area of a water mist FFFS is certainly possible as long as there is a sufficiently clear marking of the escape routes and sufficient lighting, as e.g. required by RABT.

[38] Probit functions: Functional connections between concentrations of harmful substances and period of exposure subject to the consequent mortality rate, calculated using the probit model used in statistics.

3.4.2.2 Determination of self-rescue areas

An example for the determination of self-rescue areas over route-time lines is shown in Fig. subject to the visibility conditions for an emergency exit

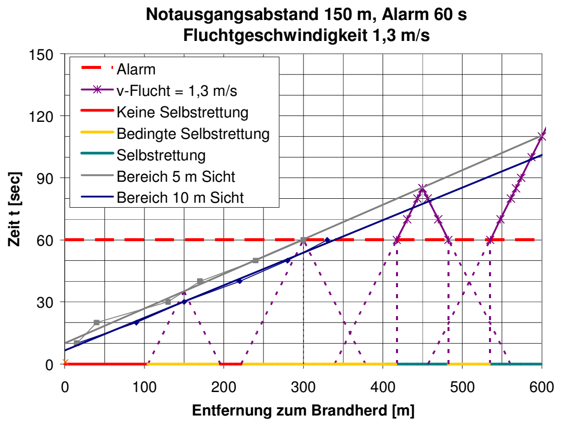


Fig.57:
Self-rescue areas [BAS 2009]

distance of 150 m. This shows the areas with successful self-rescue (green areas), determined by the way that tunnel users, at the accepted speed of escape, can get to the nearest emergency exit or portal if the escape starts as soon as the alarm has been sounded. The areas from which tunnel users can effect a self-rescue if they have already started their escape before the alarm is given by the technical equipment are shown as areas with partial self-rescue (yellow areas). No self-escape (red areas) is feasible from the areas from which given the basic speed of escape it is no longer possible to reach an emergency exit or entrance. Further effects due to high temperature and gas concentrations follow accordingly.

3.4.2.3 Traffic flow models

If, for the purposes of risk analysis, estimates from statistical traffic data and / or assumptions are insufficient, models describing the traffic flow can be used in addition in order to determine, using the vehicle occupancy rate for different traffic situations, the number of people that will potentially be affected. Here individual vehicles must be shown depending on traffic density and traffic composition.

3.5 Use of multi-criteria decision-making systems to compare fitting-out options on the basis of life cycle costs

3.5.1 General

A multi-criteria decision-making (MADM) process can be used to make decisions on an intuitive (person-related result) or analytical (using mathematical methods and values) basis. The decisive factor is that the decision maker has collated, organised and evaluated a wide range of information. Depending on the type of problem, both methods can be used to make what is supposedly the best decision.

A key element required in order to compare the individual attributes or criteria is the measuring process used. In the case of qualitative criteria it is essential to use a standard scale. Three main types of scale are available: a nominal scale (a scale in which the alternative options are only shown in comparison to each other); e.g. characteristic: Vehicle type), an ordinal scale (opportunity to arrange different measured variables; e.g. characteristic: Quality ratings) and a cardinal scale (metric measurement level; the specifications of this scale level can be shown on a quantitative basis using numbers; e.g. noise level).

The cardinal scale generally represents the scale that is the most versatile in terms of application. It allows all mathematical operations to be carried out so that clear calculations can be made. It also enables statements to be made about the relationship of data, such as "Alternative A is five times better than Alternative B". Due to the wide-ranging application of this scale it represents the basis for many MADM processes.

The Analytical Hierarchy Process (AHP) is worthy of further examination. The AHP is extremely suitable where the structuring of complex decision-making problems is concerned. The process works on the basis of decision-relevant alternatives and objectives and takes both qualitative and quantitative data into consideration. Where practical application is concerned, the process also has a relatively simple structure. The features of the AHP include simplicity of use, the ability to apply the process to single people or groups, the promotion of compromise and consensus and the communication and transparency of results.

3.5.2 The Analytical Hierarchy Process (AHP)

The AHP has three main elements: an analytical process, a hierarchical structure and a process-related approach. The analytical approach means that the method works with mathematical/logical functions, which makes it highly comprehensible for those involved in the project even without expert knowledge. The hierarchical structure leads to results that divide the decision-making problem into several levels (including all important criteria and alternatives). The process-related nature also allows the method to be restarted numerous times in order to retest decisions or to describe the entire decision-making process. It is also possible to use quantitative and qualitative information in the course of the decision.

To achieve a meaningful result, different information must be weighted in order to underline the significance of the decision made. For this reason a 9-point scale is introduced for a qualitative evaluation that allows paired and alternative comparisons. [THE 2011]

A more detailed consideration of the AHP in relation to underground infrastructure is not the object of this guidance. In this context, [THE 2011] and [THW 2011] should be referred to.

3.5.3 Processing of assessment criteria

In this section the assessment criteria for the selection of a fitting-out option for tunnel operating technology are discussed in order to be able to make a comprehensive evaluation that involves all possible parameters. The main criteria of economics, availability and user risk, which appear in the 1st level, are described and divided into sub-criteria in the 2nd and 3rd levels.

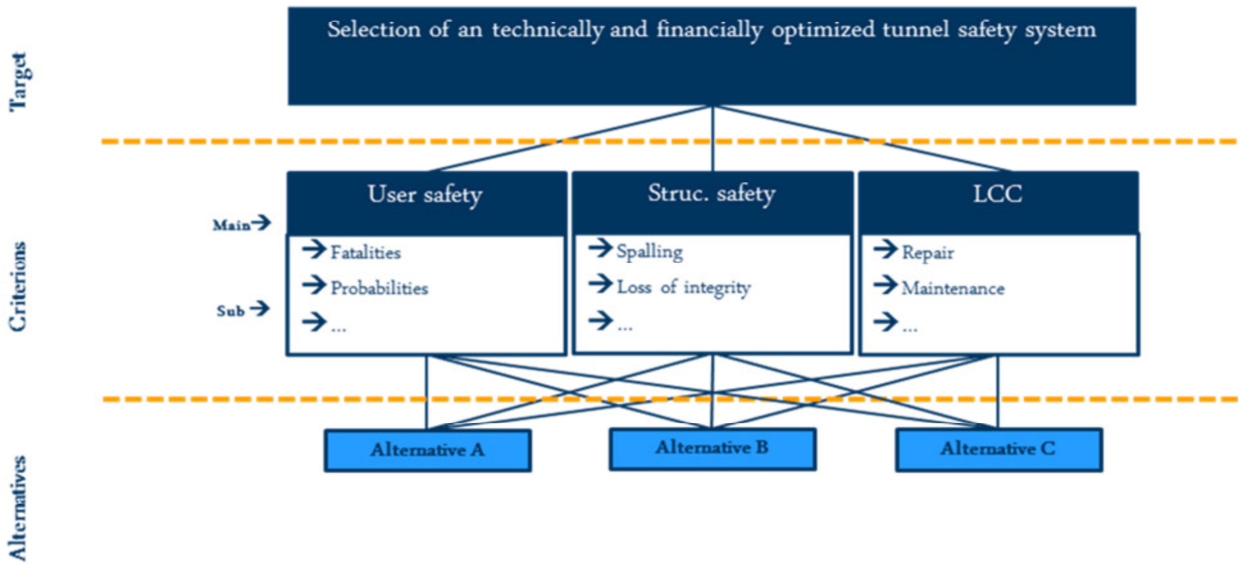


Fig. 58:
Structural development of the decision-making situation

3.5.3.1 General

The choice of tunnel operating technology throws up characteristics that initially need to be compiled by the project management team in a design phase. Due to the high degree of heterogeneity in terms of constraints and influencing factors, which are different in each project and in each environment, the meta-complex decision-making situations have no universal validity, which make it necessary to make individual decisions in each case.

In order to adapt the identified criteria to the AHP method it is also essential to divide criteria into main and sub-criteria.

3.5.3.2 Life cycle costs

Life cycle costs (LCC) can be calculated from the total sum of all costs at the beginning through to the dismantling of the tunnel operation technology. Further discussion of this topic can be found in Section 2.8.2.

3.5.3.3 Structural safety

A fire in a tunnel can, in extreme cases, lead to the temporary or permanent loss of the structure, with some considerable repercussions on the surrounding infrastructure network. Such structural damages can, under certain circumstances, lead to high ensuing costs for society as a whole, both in the form of direct costs (repair or replacement of the structure) and indirect costs (such as increased travel times due to diversion routes). For this reason, when choosing an operational component it is necessary to test its impact on the availability of the structure and to include it in an overall assessment.

The sub-criteria required differ under different circumstances, depending on the defined passive protection targets (such as temperature of reinforcement layer, tendency to spall). The sub-criteria can either be formulated in a quantitative manner, such as through numerical examinations, or a qualitative manner, through expert estimation based on the current state of knowledge.

3.5.3.4 User risk

Within a typical quantitative risk analysis the relevant occurrence probabilities for the specific structure and the corresponding scale of damage for individual scenarios are defined. The user risk that this gives represents a clear indicator for the effectiveness of a specific technical operating measure, in particular in comparison to conventional tunnel fittings.

3.5.4 Sensitivity analysis

Once the overall result of the decision problem has been identified and the weights for the various variants are available, a definitive analysis of the selected parameters and weighting information regarding the sensitivity of the decision problem can be performed. It is strongly recommended that such an analysis be performed in the case of two or more alternatives with nearly equal weights. The main objective of this analysis is to identify the impact of potential change in the weighting of individual criteria, which might lead for example to a prioritization of different parameters. So it is conceivable that in the debate regarding the effective-

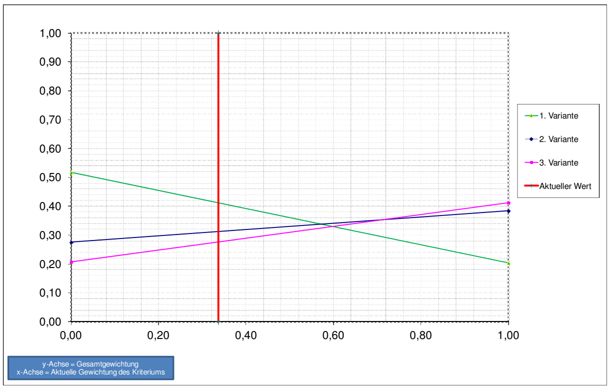


Fig. 59
Structural development of the decision-making situation

ness of a compensation measure, the cost criterion is given undue weight in comparison to the building risk and user risk. By applying a sensitivity analysis it can be shown that the ranking of different measures, -such as the comparison of the use of an FFSS with reduced ventilation compared with an conventional equipment configuration according to RABT- can be altered by changing the weighting of the cost criterion. The same possibility exists for [THE 2011] and [THW 2011] as well as for all other criteria. The following figure illustrates this on the basis of a fictitious example.

In this example, three equipment variants compete with each other, Variants 1 (green), 2 (blue) and 3 (pink). For a specific application area, these variants might represent for instance three equipment configurations, for example, a variant with an FFFS and compensated operational technology, a variant with conventional equipment, and a third variant with conventional equipment plus an FFFS. In the case shown, a decision hierarchy was built according to the situation shown in Section 3.5. All three main criteria (cost, building and users) are prioritized equally (red line at 33.33% of the total weight of the decision). Under these conditions, Variant 1 is clearly at rank 1 with respect to the others, with a total weight of about 0.4. If, in this case, the importance of the cost criterion is increased to over 60%, shifting the red line along the x-axis towards the value of 0.6, there would be a distinct rank reversal, so that Variant 1 would suddenly occupy the lowest rank.

With the AHP algorithm such an analysis is possible for all the main criteria. The decision-maker analyses individual criteria in so far as the weighting is altered minimally in small steps. This makes it clear which weighting leads to a change in the rankings. If it is only minimal changes in weighting that cause the rankings to change, this can be said to be an unstable result. In such cases the decision that has been made needs to be examined and retested.

The advantage of a guided decision, which can be performed using the AHP is, on the one hand, the transparency of the decision made: Using a sensitivity analysis, the stability or instability of a result can be measured by applying percentage changes to the weighting of the criteria. A slight change leading to a ranking change among the alternatives indicates an unstable result. In addition, the decision is transparent, traceable and can be carried out especially taking into account the prioritisation of objective perspectives.

3.6 Minimum requirements for FFFSs in tunnels

3.6.1 Selection of system technology

When choosing the appropriate system technology for the FFFS the following factors must be taken into consideration:

- Suitability of the FFFS to meet the defined protection targets
- No risk for people in the tunnel or emergency services
- Availability of individual components and the system as a whole
- Effects of the FFFS on the further operational fittings or necessary structural measures

The choice should be made following a detailed analysis by an expert and well qualified body, during which both the basic suitability and the suitability for the specific tunnel should be tested.

In every case the evidence of effectiveness must be made using fire tests, as explained in Section 0.

The mentioned explanations are to be considered as a general and simplified description as introduction to this topic. A further detailed description was not intended here consciously to allow an explanatory description. Specific system types and technologies may vary in reality from the following descriptions. A choice and evaluation of a FFFS should be done based on full scale fire test data as well as specific system parameters

The following table gives as an example an overview of the basic working mechanisms of two system technologies. It can be used as methodology to compare different types of FFFS for a specific tunnel. For information on alternative “foam based-FFFS” technology see Part 1 (Introduction), especially part 1.2 and Part 2 (Basic principles), chapter 2.4.1.

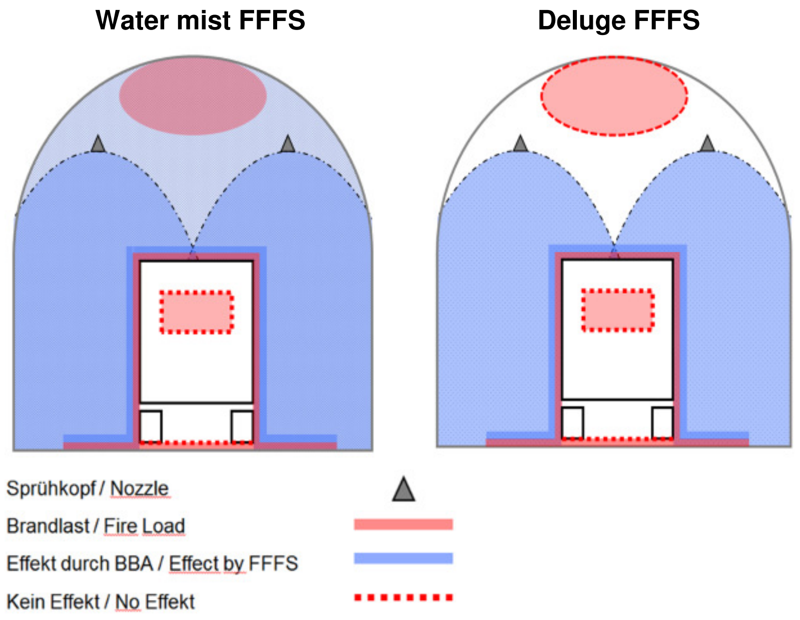


Fig. 60
Schematic representation of the effectiveness of various FFFS technologies

Overview of system features[39]		Water mist (without additives)	Deluge + open sprinklers (without additives)
Area	Ceiling (gas area)	partially	no
	Gas area below nozzles	yes	yes
	Roadway (open)	yes	yes
	Roadway (concealed)	no	no
	Concealed areas[40]	no	no
Cooling of combustion gases (see 2.4.1)		very good	good
Cooling fire load		good	very good
Cooling the building surface		yes	partially
Operation	Open Class A	direct	direct
	Class A concealed	only impact	only impact
	Open Class B	direct	direct (with limitations)
	Class B concealed	only impact	only impact
	gas fires	yes	no
	Suitability for alternative fuels	partially	partially
Absorption of radiant heat		very good	good
Asphyxiation danger		no	no
Reduced visibility		low	very low
Corrosivity of fire fighting agent		no	no
Irritation (e.g. of skin and eyes)		no	no
risk of slipping		no	no
Covering up the ground / obstacles		no	no
Covering of safety advises[41]		no	no
Contamination of the infrastructure / water[42]		no	no
Cleaning of FFFS after activation[43]		no	no
Advance warning time prior to activation[44]		no	no
Warning prior to activation		no	no
Complexity		low	low
Pipe connection		standard	standard
Pipe material		Stainless steel	Stainless steel
Moving parts in applying apparatus		no	no
Data of full scale fire tests in tunnels		yes	yes
Cleaning effort after activation		low	low
Self-cooling of the system in case of fire[45]		very good	very good

[39] The following notes are based on test results that were carried out during this research activities, on test results of other research activities and other projects, e.g. SOLIT1 and UPTUN, based on reports, technical literature as well as considerations and experiences of the consortium members.

[40] E.g. inside a vehicle, below a vehicle, brakes, covered parts of tires, boot.

[41] E.g. safety documentation and warning signs on trucks according to ADR as well as emergency route indications

[42] In case of test or faulty activation

[43] In case of test or faulty activation

[44] In case of test or faulty activation

[45] Cooling of system parts, especially cooling of piping due to fire fighting agent inside the pipe

3.6.2 Evidence of effectiveness

The basic evidence of effectiveness of FFFSs for tunnels, regardless of the system technology used, is basically gathered from full scale fire tests. Currently there is not a sufficient database for one of the commonly used system types (cf. Section 2.4) in order to be able to establish criteria with all-inclusive validity, such as the water application rate (mm/m² or l/m³/min). A detailed description of fire tests to demonstrate the effectiveness can be found in Annex 7.

Where evidence of effectiveness for a specific FFFS is available with a sufficient database, interpolations or extrapolations are possible and these can then be transferred to real tunnel situations. In this case evidence is not required for each individual tunnel. The recommended limits for transferability are explained below.

When carrying this out the following must be taken into account:

Choice of scenarios

The choice of fire scenarios for testing effectiveness should be based on a risk-based approach, in other words the scenarios should reflect the present risk and cover the worst case scenario. The test scenarios should be as realistic and reproducible as possible, for example the use of actual trucks is not advised. A recommendation for fire scenarios can be found in Section 2.5.4.

Test tunnels

Fire tests are usually carried out in special test facilities. Due to the limited availability, narrow limits are put on the choice. The test tunnel should be at least 400 m in length with the cross-section of a typical tunnel.

- Minimum length: 400 m
- Minimum height: 5.0 m
- Minimum width: 7.0 m

FFSS

Normally test systems or prototypes of FFFS are used in fire tests. However, some basic parameters must be identical to an actual installation at a later date.

- The exact type of nozzle or deluge head with documented droplet distribution and K factor must be used.
- The fire tests should be carried out at the lowest application rate and with the lowest pressure of the later installation. The difference between these parameters within the test facilities should be less than 10%.
- The distance between the nozzles or deluge heads and the fire load (truck fire load) should in a real situation be no more than 20% greater than in the test installation.
- In the tests a maximum distance between nozzles or deluge heads should be used.

Activation of the FFFS and duration of test

The activation of the FFFS should be as close as possible to conditions expected in reality. In other words, for the chosen scenario in conjunction with the ignition source, it is necessary to define the times usually needed by conventional fire detection and localisation systems[46] for this scenario to ensure secure detection and localisation.

Ventilation conditions

The ventilation conditions, comprising the type of ventilation and the air velocity, should basically correspond to the values that can be expected with the activation of the FFFS in actual real tunnel. It is not reasonable to carry out the test procedure in conditions that would be found with, for example, flowing traffic. Express mention must be made of the fact that, in particular with the use of the FFFS as a compensation measure for the fire ventilation, this and the FFFS must be compatible with each other. The longitudinal flow rate in the case of longitudinal ventilation that is normally used is approx. 2 – 3 m/s.

The influence of longitudinal flow on the FFFS medium must be checked. The spray deviation must be defined at least at 1 m/s, 3 m/s and 5 m/s.

Criteria

The efficiency of an FFFS should be judged as part of an evaluation of protection objectives. This means that the individual assessment criteria must correspond to the protection targets to be met in terms of local definition, duration and timing. It is, for example, not very sensible to establish criteria for the protection target "Possibility of self-rescue" in the direct proximity of the fire after 20 minutes. For key protection targets a dose must be given, in other words the product of the effective quantity (temperature, gas concentration etc.) depending on time unit and reaction time.

[46] This time is generally significantly longer than the 60 s required e.g. in RABT for an open liquid fire with a size of 5 MW.

Documentation

The approval test documentation is extremely important, in particular in a verification procedure for an FFFS used as a compensation measure. Alongside extensive documentation regarding the test set-up before and after the fire test, the FFFS and the outline conditions, the following values must be measured and collated at least every 2 s throughout the test. This list is not exclusive and must also include all the relevant measuring points that are required to test the protection targets.

- Temperatures near and above the fire load at 10 different places
- Temperatures in distances of 10 m, 20 m, 40 m and 100 m[47] at 5 measuring points across the cross section of the tunnel
- Radiant heat at distances of 5 m and 10 m. as well in the fire area
- Flow velocities over the entire tunnel cross-section at a minimum distance of 20 m in front of and behind the fire load
- Measurement to calculate the HRR following the oxygen usage method
- Pressure and flow rate of the FFFS
- Gas concentrations in 3 different positions at a distance of 40 m from the source of the fire

The parameter listing is not exclusive and should be expanded if necessary to monitor the safety objective. In addition, photographic, video and IR images must be made for each fire test.

A detailed description and recommendations for the measurement recording can be found in Annex 7.

Execution

The tests must be carried out by a test institute familiar with running fire tests of this size and type. At least 3 series of tests must be carried out for FFFSs in tunnels. It is recommended that the test institute is accredited in accordance with ISO/IEC 17025. In that case there is no requirement for proof of experience and competence.

3.6.3 Technical set-up

The entire FFFS must be technically designed to permanently meet the tough requirements of the tunnel environment, in order to operate reliably in the event of activation.

A more detailed description of the execution of the FFFS and the requirements for individual components can be found in Annex 3: “Engineering Guidance for fixed fire fighting systems in tunnels“ can be found under Sections 5 and 6.

3.6.4 Integration

Control of the FFFS must be carried out either as part of the (existing) control of the entire tunnel system or integrated in such a way that two-way communication can take place between the two systems. The detection and localisation system should be integrated either in the higher level overall control system or in the FFFS control system and communicate with the other former.

Control of the FFFS should have a user interface, for example in the form of a SCADA system, to allow the tunnel operator and possibly the fire services a status overview and control of the installation.

A more detailed description of the interface requirements between the FFFS and the other tunnel technical systems can be found in Annex 3.

3.6.5 Requirements for RAMS for equipment for tunnel safety systems

Currently there exist no quantitative requirements concerning the reliability, availability, maintainability and safety (RAMS) for tunnel equipment. Generally the same benchmark should be taken into account for the corresponding compensatory systems. However, it is desirable that relevant technical safety equipment and especially control systems shall undergo a proper RAMS analysis.

The development objective of the RAM parameters within the product development process of the tunnel safety system, should ensure that the failure probabilities of the components used, under expected operating conditions, are at least the same in terms of reliability characteristics, e.g. ventilation systems and other safety-related systems.

The calculation of the reliability values (failure probabilities) of individual components must be made using current norms (MIl HdBK, IEC TR 62380, NPRD 95 etc.). Field data evaluations from comparable applications must, where available, take priority as these are more meaningful.

The degree of difficulty of individual failures can be examined using an FMECA (Failure Mode Effect and Criticality Analysis) at a system level. Critical failures that lead to a non-diagnosable loss or non-availability of the safety system must be examined in greater depth and compensated for through maintenance instructions or design adjustments.

[47] The measurements and specifications are to be carried out into both directions, starting from the middle of the fire load.

3.7 Specifications for documentation, inspection and appraisal

The methods used in this guidance must be evaluated and tested by an independent third party. This institution must have sufficient experience and technical expertise in the matter of real tunnel projects along with the application and examination of individual methods. The closing report can be based on the safety report in accordance with Directive 2004/54/EG Annex II.

If components or structural elements are used then appropriate evidence for their suitability for use in tunnels must be provided. This must be checked by an independent third party.

All processes and methods must be documented in such a way that they are reproducible and verifiable for third parties. It is recommended that the documentation should form part of the safety documentation of the tunnel, as described in Directive 2004/54/EG.

Part 4 List of sources

4.1 Illustrations

Where not otherwise specified the rights of the illustrations belong to the partners of the research consortium that were involved in producing this document.

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