

AN ENGINEERING METHODOLOGY FOR PERFORMANCE-BASED FIRE SAFETY DESIGN OF UNDERGROUND RAIL SYSTEMS

ITA-COSUF

Regulations, Guidelines and Best Practice

N° ISBN : 978-2-9700858-2-9

ITA COSUF N°01 / MAY 2014



ITA COSUF

ITA Committee on
Operational Safety of
Underground Facilities

ITA COSUF n° 01 - **An Engineering Methodology for Performance-Based Fire Safety Design of Underground Rail Systems**

N°ISBN : 978-2-9700858-2-9 / MAY 2014

Layout : Longrine – Avignon – France – www.longrine.fr

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The document “An Engineering Methodology for Performance-Based Fire Safety Design of Underground Rail Systems” shall improve the safety design of underground mass rapid transit systems (MRTS). It shall fill a gap, as current safety requirements for rail tunnels and underground systems, compared to road tunnels, are less specific and lack international harmonization.

The focus of this document is on the methodology to be followed while analyzing the effectiveness of any safety measure of MRTS. The performance-based approach aims at integrating the different methods to achieve a safe tunnel design including standards and norms. As the topic is complex, the methodology at hand needs further refinement in the future and is considered as a first proposal only.

The document was established by “Activity Group 2 - Regulations, guidelines and best practice” of the Committee on Operational Safety of Underground Facilities (ITA-COSUF) of the International Tunnelling and Underground Space Association (ITA) under the lead of Dr Peter Reinke (HBI Haerter Consulting Engineers, Switzerland) and Dr Marco Bettelini (Amberg Engineering Switzerland) and the support of further collaborators.

The authors would like to express their gratitude to the following persons for reviewing the report (in alphabetical order): Felix Amberg (Amberg Engineering, Switzerland), Andreas Busslinger (HBI Haerter, Switzerland), Gary Clark (Atkins, United Kingdom), Ben van den Horn (Arcadis, The Netherlands), Robert Lassy (Wiener Linien, Austria), Roland Leucker (STUVA, Germany), Stig Ravn (COWI, Denmark), Jörg Schreyer (STUVAtec, Germany), Fathi Tarada (Mosen, United Kingdom).

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1 >> INTRODUCTION

Although accident rates in road and rail tunnels are low and fires are not especially common in tunnels, the consequences of fires in a tunnel can be far more severe than for similar fires in the open air. Large tunnel fires have shown the devastating effects of smoke and heat on people escaping from tunnels. Additionally, the fires caused severe damage to the tunnel structure and financial losses due to interrupted operation. As a consequence, the required fire safety measures for tunnel infrastructures have become more stringent in recent years.

Due to the recent fire incidents, safety guidelines for road tunnels have reached a high level of detail and exhibit a substantial degree of international harmonisation. In contrast, safety requirements for rail tunnels and underground systems are limited to more basic and less uniform requirements (e.g. TSI [1], UIC [3]). The standards for smoke control in metro systems, for example, might vary even within a country from project to project.

Figure 1 provides an overview of tunnel-specific railway risks ([1]) and the different types of measures for risk mitigation.

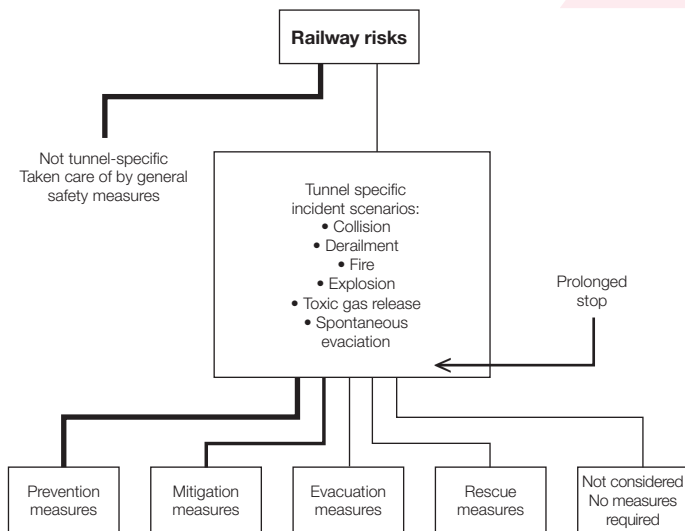


Figure 1: Overview of railway risks and mitigation measures (from [1])

National regulations (e.g. NFPA130 [11] or SIA 197/1 [12]) provide at times quite specific minimum requirements, e.g. with respect to the maximum allowable distance between emergency exits and to the minimum width of escape paths. Design work mostly tends to fulfil the minimum requirements, implicitly or explicitly assuming that this will automatically provide for an adequate safety level. However, the following limitations are noted:

- The minimum requirements are not always sufficient for any specific project. Depending on project-specific issues (such as, for example, rolling stock constraints, mixed traffic with dangerous goods, etc.) more stringent safety measures could be required.
- The minimum requirements are sometimes extremely demanding and can be achieved only at disproportionate costs. Alternative measures must be identified and a specific, accepted engineering analysis is required for proving that the minimum safety requirements are satisfied.

Even though fires in rail and metro tunnels are rare, design objectives with respect to fire safety need to be defined, harmonised among the various stakeholders, mutually accepted and implemented. When these are not specified in detail, the following disadvantages may result:

- The planning and the process of approval by authorities might become unnecessarily time consuming, uncertain with respect to results and inefficient.
- The resulting measures often depend on the individual preferences of the safety authority, leading to a substantial uncertainty regarding the expected costs for the project owner.
- Among different projects, an unbalanced provision of measures leads to unbalanced, inefficient investments. Substantially different standards and resulting costs even for new underground lines might prevail for different projects in a country.
- There are no standards or reference requirements for insurances.

In some metro and rail projects, the uncertainties about the requirements for fire safety have become a major project risk for the project owner, the planners and the contractors. Therefore, it is desirable to specify methods for the planning of fire safety of metro and underground rail systems and to promote an international harmonisation of guidelines. The objective should be to focus the analysis on “reasonable worst-case incidents” and to reduce the variability of cost-benefit-ratios of fire safety measures in underground projects.

2 >> OBJECTIVES / 3 >> LIMITATIONS

2 OBJECTIVES

This document provides an engineering methodology for performance-based fire safety design and design verification of underground rail systems. Rather than proposing requirements and specifications for any specific safety-related aspect of tunnelling, the focus is on the methodology to be followed while analysing the effectiveness of any safety measure. This engineering guidance is intended e.g. for handling the following issues on a project-specific basis:

- Verification of given minimum safety requirements and identification, if needed, of possible project-specific improvements,
- Verification of alternative safety designs allowing for a safety-based assessment of the relative merits of design alternatives and for the functional verification that minimum safety requirements are met.

The performance-based approach presented herein is not intended as a replacement of prescriptive approaches which are, in general, the results of national and international regulations. Indeed, the performance-based approach aims at integrating the different approaches to a safe tunnel design:

- In general, minimum requirements define the safety level for comparatively “simple” tunnels. More complex systems, with various non-regulated features and the potential for severe consequences during incidents, must be integrated with adequate safety measures. These measures may be in excess of the minimum requirements.
- Verification of alternative safety systems or measures offering an equivalent level of safety (as proposed for example in [11]¹) and/or evaluation of more economical designs.

In addition to an overall methodology, this document presents a limited set of functional requirements regarding the fire safety of underground rail systems for passenger transportation with stations. These functional requirements are presented to illustrate the application of the performance-based fire safety design. Examples of functional requirements or design objectives are as follows:

- Provide tenable conditions for the self-rescue and intervention of rescue and fire services,
- Provide a “fair chance for escape” (“Whenever incidents occur, the persons affected must have a fair chance of survival” [16]).

These objectives are discussed in more detail in section 5.2, along with a number of other possible requirements.

Another objective of this guideline is to trigger a discussion on an internationally harmonised refinement of fire safety requirements for underground parts of rail systems with stations and to promote their application in regulations and projects.

3 LIMITATIONS

This guideline focuses on fire safety of underground railway systems for passenger transportation with underground stations. In particular, it addresses functional objectives for smoke control during the self-rescue and intervention phases of an emergency. Among others, the following topics shall not be addressed:

- Definition of fire resistances and structural requirements,
- Specification of measures for smoke control,
- Specification of measures for rolling stock,
- Consideration of different scenarios regarding intervention of fire and rescue services,
- Consideration of other technical or operational disturbances,
- Elaboration of underlying basics and investigations of the approach (e.g. numerical simulation of fires, quantitative risk analysis).

There is a wide range of different types of underground railway systems. People mover, cable cars, light rail trains, trams, metros, (sub-)urban railways, heavy rail trains, heavy long-distance railway trains, etc. differ, for example, in size, speed, number and density of passengers, fire load, degree of automation, etc. Some railway networks combine passenger with freight transportation. So there is wide range of parameters and different features to be considered. As a result, design objectives for fire-safety measures might differ significantly for the different types of underground railway systems. This methodology is intended to be used for most of underground railway systems with passenger transportation.

¹ NFPA 130, 2010, Chapter 1.4: Equivalency: “Nothing in this standard is intended to prevent or discourage the use of new methods, materials, or devices, provided that sufficient technical data are submitted to the authority having jurisdiction to demonstrate that the new method, material, or device is equivalent to or superior to the requirements of this standard with respect to fire performance and life safety.”

4 >> DEFINITIONS AND REFERENCED DOCUMENTS

4.1 DEFINITIONS

Definitions for selected terms used in this document are given below. A more comprehensive list of definitions relevant to the subject addressed here is given, for example, by TSI [1], NFPA 130 [11] or ISO [5].

Design fire Features of the fire to be considered for safety analysis and proof of achievement of fire safety objectives (e.g. defining fire load, temporal evolution of heat release rate, rate of smoke and soot release, etc.)

Egress Exiting from a zone exposed to harmful effects of a fire to a safe area or point of safety

Emergency scenario Scenarios shall consider the location, start-time and temporal evolution of size of the fire and the related sequence of emergency actions (e.g. time of detection, alarm, train stop, ventilation activation, etc.)

Safe area / Point of safety A place inside or outside a tunnel or station where all of the following criteria apply:

- (a) Conditions are survivable;
- (b) Access for people is possible aided and unaided,
- (c) People may accomplish self-rescue, if possible, or may wait to be rescued by the rescue services using procedures detailed in the emergency plan;
- (d) Communication shall be possible (mobile phone, fixed connection)

Tenable environment In a transportation system, an environment that permits the self-rescue of occupants during a specific period of time with respect to heat, visibility and air quality

4.2 RELATED STANDARDS AND GUIDELINES

- [1] European Commission, “Commission Decision of 20 December 2007 concerning the technical specification of interoperability relating to safety in railway tunnels in the trans-European conventional and high-speed rail system”, 2008/163/EC, 2008
- [2] European Commission, “Commission Decision of 21 December 2007 concerning the technical specification of interoperability relating to ‘persons with reduced mobility’ in the trans-European conventional and high-speed rail system”, 2007
- [3] European Committee for Standardization (CEN), “Railway applications — The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Basic requirements and generic process”, European Norm EN 50126-1:1999, 1999
- [4] Union International des Chemin Fer (UIC), “UIC-Codex 779-9 - Safety in Railway Tunnels”, August 2003
- [5] International Standards Organization ISO, “Fire safety engineering - Part 1: Application of fire performance concepts to design objectives”, ISO/TR 13387-1, 1999
- [6] International Standards Organization ISO, “Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data”, ISO 13571, 2012
- [7] German Ministry of Transportation, “Verordnung über den Bau und Betrieb der Strassenbahnen (BoStrab) - Regulation on construction and operation of underground fixed guideway transit and passenger rail systems”, in German, 1987 with last modification in 2007
- [8] German Ministry of Transportation, “Technische Regeln Strassenbahnen – Brandschutz (TR Strab BS) - Technical standard for tramways – fire protection (TR Strab BS)“, Edition: 21.08.2013
- [9] EBA – Eisenbahn-Bundesamt, “Anforderungen des Brand- und Katastrophenschutzes an den Bau und den Betrieb von Eisenbahntunneln – Requirements of fire and emergency management in rail tunnels“, in German, 01.07.2008
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- [11] NFPA 130, “Standard for fixed guideway transit and passenger rail systems”, National Fire Protection Agency, 2010
- [12] Swiss Tunnel Code SN 505 197/1, SIA 197/1:2003. Design of Tunnels - Railway Tunnels, 2003

4 >> DEFINITIONS AND REFERENCED DOCUMENTS

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- [14]** Ministère des transports, de l’équipement, du tourisme et de la mer, « Arrêté du 22 novembre 2005 relatif à la sécurité dans les tunnels des systèmes de transport public guidés urbains de personnes », Journal officiel du 9 décembre 2005 (in French)
- [15]** Le ministre d’Etat, ministre de l’écologie, du développement et de l’aménagement durables, et la ministre de l’intérieur, de l’outre-mer et des collectivités territoriales, « Arrêté du 24 décembre 2007 portant approbation des règles de sécurité contre les risques d’incendie et de panique dans les gares », Journal officiel du 16 avril 2008 (in French)
- [16]** Swiss Federal Office of Transport FOT, “FOT Safety Concept”, 1 January 2009

4.3 REFERENCED PUBLICATIONS

- [17]** Blennemann, F., Girnau, G. (Eds.), Fire Protection in Vehicles and Tunnels for Public Transport, 2005
- [18]** Schreyer, H. Gerhardt, P., “Notfallszenarien für Tunnelanlagen des ÖPNV – Emergency scenarios for public transportation tunnels”; Forschung + Praxis Band 40; STUVA Jahrestagung in Dortmund, Germany, 2003
- [19]** Thematic Network FIT – Fire in Tunnels, “Technical Report – Part 1 - Design Fire Scenarios”, Rapporteur A. Haack, Thematic Network FIT ‘Fire in Tunnels’ is supported by the European Community 5. Framework Programme ‘Competitive and Sustainable Growth’ Contract n° G1RT-CT-2001-05017, 2005
- [20]** Haack, A., Schreyer, J., “Emergency Scenarios for Tunnels and Underground Stations in Public Transport”, Fourth International Symposium on Tunnel Safety and Security, Frankfurt, Germany, March 17.-19., 2010
- [21]** Bettelini, M., Rigert, S., “Emergency Escape and Evacuation Simulation in Rail Tunnels”, ISTSS - Tunnel Safety & Security, 5th International Symposium, 14-16 March 2012 New York, USA.
- [22]** Haack, A., “Real fires and design fires”, Proceedings of the Jornada Técnica sobre Fuego en Túneles, Barcelona, Spain, 5 May 2011
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5 >> METHODOLOGY

5.1 OVERVIEW

The guideline presents an approach which has been applied in several European projects (e.g. methodology used for projects in Belgium, Germany, Spain and Switzerland). It is proposed to address the following main tasks:

A. As a first task, all relevant incident and accident scenarios are screened on a qualitative basis according to their frequency and severity. Low-risk scenarios are accepted while additional safety measures are investigated for the remaining scenarios. Scenarios requiring a detailed analysis are identified. The result is a general evaluation of the severity of all possible hazards for the project in question and the identification of the most relevant scenarios.

B. Based on the result of the previous task, if needed, a number of scenarios can be investigated in a detailed manner by means of comprehensive simulation. If necessary and depending on the findings from the detailed analysis, the benefits of additional safety measures are investigated.

Eight key steps are defined as follows:

1. Specification of basic fire design objectives
2. System and problem definition,
3. Identification of relevant scenarios,
4. Definition of fire safety measures,
5. Preliminary screening of scenarios and identification of critical scenarios,
6. Detailed analysis of critical scenarios,
7. Evaluation of possibly adapted safety measures based on detailed scenarios,
8. Assessment and conclusions.

The different steps are briefly presented in the following chapters. The approach is illustrated in Figure 2.

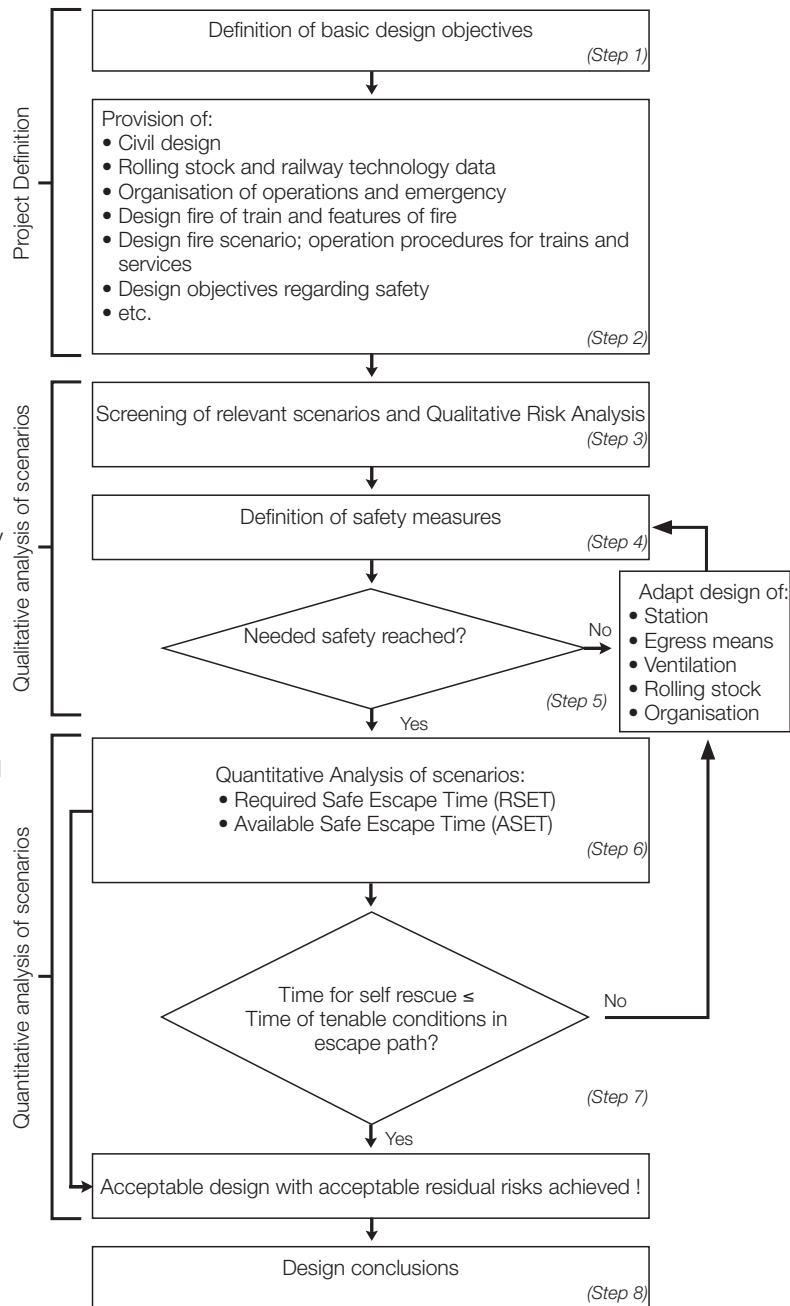


Figure 2: Overview of methodology

5.2 DEFINITION OF BASIC DESIGN OBJECTIVES

In a first of eight steps, the basic design objectives shall be specified. Safety objectives could be formulated as follows:

- Protection of human life superior to prevention of loss of property,
- Provision of tenable conditions during self-rescue phase,
- Identification of cost-effective measures, which allow for a positive balance between additional costs and reduction of direct and indirect cost due to incidents (including loss of human lives),
- Minimization of overall costs (including loss of human lives),
- Specification of maximum allowable loss threshold (loss of human lives, damage to infrastructure and property, loss of revenue, further material damage to society),
- Minimization of the environmental impact of the fire and fire protection
- Minimization of loss of availability for critical infrastructures.

A generic safety objective is formulated in NFPA 130 [11] for fires: “Systems shall be designed, constructed and maintained to protect occupants who are not intimate with the initial fire development for the time needed to evacuate or relocate them or to defend such occupants in place during a fire or a fire-related emergency”.

More generally, applicable and precise objectives of a performance-based safety analysis can be formulated based on the guideline published by the Swiss Federal Office of Transport (FOT, Switzerland’s safety authority for railways, tramways, cableways, boats, buses and trolley buses): “Whenever incidents occur, the persons affected must have a fair chance of survival” (principle of “fair chance”; [16]).

There is no general definition of the concept of “fair chance”. This must be adapted to the specific project. In general, it is accepted that not all persons on the train are able to rescue themselves in a case of emergency. Passengers may comprise of very young, elderly persons and/or impaired people. The common analysis focusses on:

- “Average” persons with “normal” mobility,
- Passengers and staff with no significant physical or mental problems (e.g. normally seeing and hearing),
- Persons with rational behaviour (i.e. no panic, no persons drunk or drug-dependent).

Frequently, an implied definition is given in NFPA 130 [11] where the concept of “fair chance” is implicitly related to the escape characteristics specified in the standard, such as escape velocity on corridors and on stairs. It is clear that e.g. persons in wheelchairs or visually impaired users might not be able to achieve the assumed escape speed.

Clearly persons with reduced mobility (PRM) [2] cannot be ruled out a priori. Under certain conditions (e.g. in case of a train stop in a tunnel) their chance of self-rescue would be extremely low without significant additional safety measures. Such situations must be discussed with the infrastructure owner during the project-definition phase.

The analysis is generally based on more specific, directly measurable objectives, expressed e.g. in terms of smoke concentration, radiant and convective load on the users and pollutants concentration. This aspect is treated in section 5.5.2.

5.3 SYSTEM AND PROBLEM DEFINITION

In a second of eight steps, the system to be analysed must be defined in sufficient detail and the objectives of the investigation must be clearly identified and formulated. The features of the underground system must be properly identified and described, with respect to:

- Civil and safety design of stations,
- Civil and safety design of tunnel,
- Rolling stock features (e.g. length, number of persons, maximum load, free-run characteristics in case of fire, detection and extinction facilities, communication facilities, etc.),
- Rail infrastructure and control,
- Traffic (e.g. number and type of trains, crossings and following distance, etc.),
- Operation rules,
- Organisation (emergency management and intervention).

The required specifications depend intimately on the objectives of the investigation.

5.4 DEFINITION, SCREENING AND ANALYSIS OF SCENARIOS – QUALITATIVE SCENARIO ANALYSIS

5.4.1 Approach

Relevant scenarios, which require a refined investigation, need to be identified. The main elements of the investigation are as follows:

1. All safety-relevant scenarios should be listed and briefly described. The selection should be as representative as possible for the whole spectrum of scenarios potentially relevant for the specific investigation.
2. The probability and the loss potential for all scenarios are estimated, based on available experience, simple engineering analysis or expert judgement. The results are represented in a probability-consequences diagram, which allows for an overview of the level of risk and of a ranking of the scenarios.
3. Based on the results, additional or adapted safety measures are accounted for based on the findings from the previous step.
4. The risk evaluation is adapted in an iterative manner.

Scenarios with a low level of risk can be accepted as residual risk, without additional investigations. Scenarios with a high level of risk must be investigated in detail and mitigated by appropriate measures.

5.4.2 Scenario definition

In the third of eight steps of the analysis, the spectrum of scenarios should be as broad as possible, depending on the specific objectives of the investigation. Passengers and staff in underground rail systems might be endangered, amongst others, by the following incidents (see Figure 1):

1. Train fire and stop in station,
2. Train fire and stop in tunnel,
3. Derailment,
4. Collision with obstacle and/or other trains,
5. Cable fires,
6. Fire of elevators,
7. Fire in technical rooms,
8. Fire in station commercial areas,
9. Collapse of infrastructure,
10. Overcrowding,
11. Explosions,
12. Terror.

The focus of this document is on underground train fires (items 1 and 2 above). Despite the very low frequency, such events should be included in any safety analysis because they may lead to a significant release of heat and smoke and may put a very large number of persons at risk.

In most cases, train fires are considered to be the main risk in rail tunnels and underground stations compared to all other incidents mentioned above [1]. Consequently, in state-of-the-art underground systems, it is required to reduce the probability of fires occurring on trains and to limit the harmful consequences of them. These measures of prevention and limitation of the consequences of incidents address the following system aspects:

- Infrastructure, i.e. tunnels and stations,
- Rolling stock,
- Operation and organisation.

It is impossible to eliminate risk by considering every possible event scenario, particularly, considering the possibility of human error. It is required to focus on the most probable incidents and/or those with significant consequences. The measures shall provide a sufficient level of safety based on “reasonable worst case” scenarios and pragmatic design objectives.

Therefore, a further limitation could be to focus on train fires in stations only. A detailed analysis for the German underground networks came to the conclusion that only a scenario of a burning train reaching the next station should be considered as standard fire scenario (see [18]). The approach of omitting scenarios with burning trains stopped in a tunnel section differs from the American norm NFPA 130 or others (see [11], [13], [14]). In [11] it is stated, for example, that any tunnel section with a length of more than 305 m shall be provided with a mechanical emergency ventilation system. The proposed approach of this guideline specifies only the design

methodology but not the measures to fulfil the requirements. This means that, for example, mechanical ventilation is not prescribed but, upon engineering analysis, a natural ventilation, a mechanical ventilation, a spacious station and tunnel design with substantial smoke reservoirs, an advanced fire extinguishing system on-board of vehicles or in the station (water mist, sprinkler) need to be considered as alternative solutions to fulfil these design objectives. Thus, this guideline provides flexibility in choosing the most appropriate set of measures compared to certain norms and guidelines.

In summary and in most cases, only a train fire in the station needs to be considered with respect to maintaining tenable air conditions during the phases of self-rescue and intervention by fire and rescue services. However, exceptions should be considered. An example is represented by tunnels, where the emergency brake is not inhibited while traveling through a tunnel. In such situations, the risk of immediate stop of a burning train in the tunnel is obvious, since the train passenger may immediately activate the emergency brake as they detect flames or smoke. Another example is tunnels with combined use for passenger and freight transportation and the related risk of release of dangerous goods. In these systems, train fires are of relevance not only at stations but in tunnels as well.

5.4.3 Definition of fire safety measures

In a fourth of eight steps, the intended safety measures shall be defined.

5.4.4 Analysis in qualitative manner

In a fifth of eight steps, only a limited number of scenarios shall be investigated in depth. The resources available shall be focused on the truly safety-relevant scenarios. Therefore, a preliminary ranking is needed. Based on EN 50126 [3] the frequency can be subdivided in classes according to Table 1.

5 >> METHODOLOGY

Table 1: Frequency of occurrence of hazardous events

CATEGORY	DESCRIPTION
Frequent	Likely to occur frequently. The hazard will be continually experienced
Probable	Will occur several times. The hazard can be expected to occur often
Occasional	Likely to occur several times. The hazard can be expected to occur several times
Remote	Likely to occur sometime in the system life circle. The hazard can reasonably be expected to occur
Improbable	Unlikely to occur but possible. It can be assumed that the hazard may exceptionally occur
Incredible	Extremely unlikely to occur. It can be assumed that the hazard may not occur

For practical applications the classes shall be specified as ranges in event per years. The consequences can be estimated in terms of number of victims and/or consequences (see Table 2).

Table 2: Hazard severity level

SEVERITY LEVEL	CONSEQUENCE TO PERSONS OR ENVIRONMENT	CONSEQUENCES TO SERVICE
Catastrophic	Fatalities and/or severe injuries and/or major damage to the environment	
Critical	Single fatality and/or severe injury and/or significant damage to the environment	Loss of a major system
Marginal	Minor injury and/or significant threat to the environment	Severe systems damage
Insignificant	Possible minor injury	Minor system damage

Here too, the classes must be defined in a quantitative manner, for example, as ranges in victims/case.

Table 3: Frequency and severity classes (Example)

Frequency of occurrence		Severity level	
	Cases / 100 years		Victims / case
Frequent	> 100	Insignificant	0
Probable	10 - 100	Marginal	1
Occasional	1 - 10	Critical	2 - 9
Remote	0.1 - 1	Very Critical	1 - 50
Improbable	0.01 - 0.1	Catastrophic	> 50
Incredible	< 0.01		

Based on the frequency and the severity level of consequences, all scenarios considered can be arranged in the matrix of Table 4 (example only).

Table 4: Typical example of risk evaluation and acceptance for different risk levels

Frequency of occurrence of a hazardous event	RISKS LEVELS			
	Undesirable	Intolerable	Intolerable	Intolerable
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Tolerable
Incredible	Negligible	Negligible	Negligible	Negligible
	Insignificant	Marginal	Critical	Catastrophic
	Severity of Hazard Consequences			

Risk Evaluation	RISK REDUCTION/CONTROL
Intolerable	Shall be eliminated or reduced
Undesirable	Shall only be accepted when risk reduction is impracticable and with the agreement of the Railway Authority
Tolerable	Acceptable with the agreement of the Railway Authority
Negligible	Acceptable without any agreement

Scenarios in the “Negligible” class shall be accepted without further investigation. For all other classes some degree of investigation, clearly increasing from “Tolerable” to “Intolerable”, is required for evaluating measures for risk minimization. For every set of safety measures the consequences on the scenario classification are verified.

For all scenarios classified as “Intolerable” or “Undesirable” a detailed elaboration of measures and investigation is needed. A possible classification of hazards, holding for a particular investigation, is presented in Table 5

Table 5: Example of risk assessment of different scenarios

FREQUENCY							
			I	II	III	IV	V
	> 100	A Frequent					
	10 - 100	B Probable	F3				
	1 - 10	C Occasional	I1	I2, P1, P2			
	0.1 - 1	D Remote	A1	19, 110	15, F1	14	13
	0.01 - 0.1	E Improbable	A2		18, A3	F2, 16, A4	
	< 0.01	F Incredible					17
	(Cases/100y)						
		Victims/case	Insignificant	Marginal	Critical	Very Critical	Catastrophic
			0	1	2-9	10-50	> 50
			SEVERITY LEVEL				

In Table 5, the codes F3, I1, I2, P1, P2, etc. indicate scenarios which have been identified during the analysis (not explained here further; examples only). The quantification of the frequency, the severity level and the allocation of acceptance levels (“tolerable”, “undesirable”, “intolerable”, “negligible”) is not constant but depends on the nature and location of the project. In fact, the definition and acceptance of risks depends on the social-political setting of a project. The allocation of acceptance levels varies from country to country.

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5.5 DETAILED ANALYSIS OF CRITICAL SCENARIOS – QUANTITATIVE SCENARIO ANALYSIS

5.5.1 Approach

Based on the findings from the preliminary screening according to Chapter 5.4.4, a number of scenarios must be investigated in a detailed manner. It is assumed herein that the determinant scenarios are represented by train fires. This is usually the case, but the methodology can be applied to other scenarios too, e.g. for cases where natural catastrophes or dangerous-goods scenarios are determinant. The main steps are as follows:

1. Detailed scenario definition (train position, number of persons, fire-development characteristics etc.),
2. Detailed analysis of the environmental conditions, including visibility, temperature, radiant load etc.,
3. Detailed analysis of the evacuation process (self-rescue and assisted evacuation),
4. Result analysis; this is based on the verification of the tenability conditions along the escape path during the whole evacuation phase,
5. Based on the results, additional or adapted safety measures are accounted for, based on the findings from the previous step,
6. The analysis is adapted in an iterative manner.

A principal element of the approach presented in this guideline is the balancing of the time for self-rescue and the time for sufficient control of smoke. This approach allows reaching a certain level of safety most efficiently. The required balance between rescue time and time of acceptable smoke control is illustrated in Figure 3.



Figure 3: Balance between time for self-rescue and the time for proper control of smoke

The main objective of this approach is to ensure a tenable environment in the station during the phase of self-rescue. The additional objective is to provide acceptable conditions for rescue and fire services. For example, measures for improvement of self-rescue (e.g. wider and more stairs) reduce the required efforts for smoke control. Vice-versa, a better smoke control allows acceptance of a longer phase of evacuation. In other words, in order to improve fire safety, resources may be invested in improved measures for evacuation or in a better control of smoke propagation.

5.5.2 Example of specifying quantitative objectives for smoke removal

The fire of a rail vehicle will produce smoke according to the specifications of the design fire. From the fire location the smoke will rise and spread along the ceiling of the station box. If flow disturbances are limited and if openings, shafts, etc. are absent, the smoke will accumulate below the ceiling and concentrate in a layer of hot gases. This layer of smoke is characterized by high temperature, low visibility, high concentration of carbon-monoxide and carbon-dioxide, etc. In the highly concentrated smoke layer, people cannot survive. Below this layer a zone of colder and non-life-threatening air might remain for an extended period of time. In a simplified manner, it may be assumed that for most fire incidents, this stratified layer of smoke will remain above the platform during the initial phase of a train fire.

The knowledge of the impact of fire gases on humans that can be found in the literature is rather extensive regarding the life threatening components. According to the international standard ISO 13571 "Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data" [6] the following threats should be accounted for:

- Exposure to convective heat.
- Exposure to radiant heat.
- Inhalation of irritant gases.
- Inhalation of asphyxiant gases.

The individual evaluation of inhalation of asphyxiant gases is based on the concept of fractional effective dose FED and the exposure to irritant gases on the concept of fractional effective concentration FEC [6].

A tenable, low-concentration smoke layer needs to exhibit a minimum height and air quality. For the phase of self-rescue and the later phase of intervention by rescue and fire services the layer is characterized by the features according to Table 6.

Table 6: An example of a specification for a tenable, low-concentration smoke layer along the platform of the station according to [17]

ASPECT	SPECIFICATIONS SELF-RESCUE (SRP)	SPECIFICATIONS INTERVENTION PHASE (IP)
Duration (depends on analysis)	t_{SRP} (e.g. $0 \text{ min} < T_{SRP} < 5 \text{ min}$)	t_{IP} (e.g. $15 \text{ min} < T_{IP} < 30 \text{ min}$)
Height above platform	$H \geq 2.5 \text{ m}$	$H \geq 1.5 \text{ m}$
Distance of visibility	$S \geq 10 \text{ m}$ (= optical density of 0.13 m^{-1} in 40 lx illuminance)	
Temperature	$T \leq 50^\circ\text{C}$	
Concentration CO^2	$C \leq 1 \text{ Vol.-%}$	
Concentration CO	$C \leq 500 \text{ ppm}$	

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The requirements concerning the height of the low-concentration smoke layer are illustrated in Figure 4.



Figure 4: Objectives for maintaining a layer of low smoke concentration above platform (times are indicative only and depend on the analysis of smoke behaviour and evacuation)

The characteristics of the design fire might vary. In most cases, however, the visibility is the most critical parameter, i.e. the visibility determines the most extreme expansion of the hazardous smoke layer. Typically, if a sufficient visibility is maintained, the toxic or thermal conditions are acceptable. In addition to the above specifications regarding the platform, additional requirements need to be fulfilled for additional spaces (stairs, emergency exits, mezzanine level, etc.).

The application of tenability criteria at the immediate perimeter of a fire is impractical. The zone of tenability should be defined to apply outside a boundary away from the perimeter of the fire. This distance will be dependent on the fire heat release rate. For example, it could be as much as 30 m ([11]).

In the design process of a station, the above objectives for smoke removal need to be verified by numerical analysis. Three-dimensional, CFD-analysis (computational fluid dynamics) is required to investigate the smoke stratification and propagation in a station and to confirm the achievement of a tenable layer with low smoke concentration along the platform of the station.

5.5.3 Detailed scenario definition

In a sixth of eight steps, a more refined definition of scenarios is required for carrying out the detailed analysis. Aspects to be accounted for include:

- Train stopping position,
- Number, location and characteristics of the persons on the train,
- Fire location on the train, fire development in time and pollutant-generation characteristics,
- Initial and boundary conditions of underground aerodynamics (e.g. mechanical ventilation, meteorological pressure difference between the portals, train induced pressure changes, thermal effects etc.),

- Time development, including fire initiation, fire development, detection, train stop, information to the passengers, activation of ventilation, intervention.

Further details to be specified depend on to the particular approach used for simulating fire and smoke propagation and for analysing the evacuation process.

5.5.4 Evaluation of possibly adapted safety measure based on detailed scenarios

In a seventh of eight steps, the performance of measures shall be evaluated based on detailed scenarios. In order to limit the consequences of fire incidents in underground stations, the following measures need to be considered and possibly adapted:

- Reliable and early detection of fire,
- Rapid alarm and activation of measures:
 - Fire suppression and extinction of fire,
 - Smoke control,
 - Passive or active ventilation of emergency exits and rescue ways.
- Rapid self-rescue and evacuation of people to a safe location by support through:
 - Lighting,
 - Signage,
 - Communication and alarm system
 - Organisation of operation and emergency staff
 - Training.
- Traffic monitoring equipment,
- Reliable power supply.

With respect to measures for “smoke control”, the following passive or active measures can be employed:

- Limitation of smoke propagation by smoke curtains, doors,
- Limitation of smoke propagation by ventilation of corridors and platforms,
- Increase of “storage volume” for smoke by reservoirs by high ceiling of stations,
- Smoke removal by smoke extraction shafts / openings in ceiling,
- Smoke removal by mechanical ventilation.

According to the EU’s Decision 2008/163/EC, 2008 [1], the priorities are as follows (see Figure 5): “The line of defence for the promotion of safety in tunnels comprises four successive layers: Prevention, mitigation, evacuation and rescue. The largest contribution is in the area of prevention followed by mitigation and so on. A major feature of railways is their inherent ability to prevent accidents through the traffic running on a guide-way and being controlled and regulated using a signalling system. The layers of safety combine to produce a low level of residual risk.”

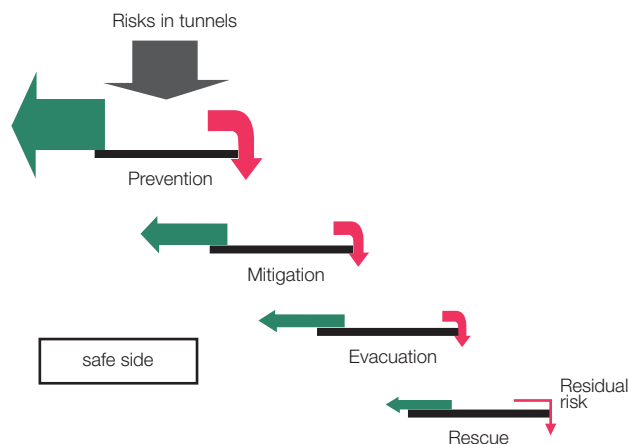


Figure 5: Line of defence for the promotion of safety in rail tunnels [1]

5.5.5 Assessment and conclusions from scenario analysis in a quantitative manner

In the last of eight steps, the safety level shall be (re-)assessed. Fire safety objectives are achieved, if the conditions along the escape path are acceptable during the whole escape process. Based on these results the scenarios can be subdivided in three categories:

1. Scenarios entirely mastered by the given safety system,
2. Scenarios partially mastered by the given safety system. This could depend, e.g. on the number of persons on the train, on fire development characteristics or on meteorological conditions. This corresponds broadly to a safety level, where risks should be minimized as low as reasonably practicable (ALARP) by means of adequate measures,
3. Scenarios not mastered sufficiently by the given safety systems (residual risk), i.e. the scenarios leading to a substantial number of victims and extensive damages. Adapted or additional measures are required.

These conclusions, particularly the extent of the residual risk, shall be presented in a very clear and transparent manner to the infrastructure's owner, operator and safety authority.

6 CONCLUSIONS

In rail tunnels and underground systems severe fires with fatalities and significant damage to property are comparatively rare events. However, they cannot be excluded. The consequences of fires might be catastrophic and more severe in train tunnels compared to road tunnels due to the extreme density of passengers.

The minimum level of safety is often defined by common practice or by specific guidelines. Adequate measures for handling such events need to be implemented in underground systems.

For the project-owner, designer and contractor, ill-defined design standards pose a significant risk. Therefore, harmonised standards are needed. The objective is to eliminate uncertainties during the planning process. This guideline presents a framework for a more systematic approach for carrying out performance-based safety analysis of rail systems. With the approach presented, the design phase can be appreciably shortened and more reliably handled. In future revisions, the approach shall be refined and updated.

7 >> APPENDIX (INFORMATIVE)

This appendix provides additional information on the following topics:

- Focus on train fires in stations
- Analysis of fire and smoke propagation
- Analysis of evacuation process

This information is purely informative and is provided by several examples.

7.1 FOCUS ON TRAIN FIRES IN STATIONS

A detailed analysis for the German underground networks came to the conclusion that only a scenario of a burning train reaching the next station should be considered as standard fire scenario (see [18], [8]). The measures to cope with this scenario allow addressing other risks associated with stations as well (e.g. cable fires, fire in technical rooms).

According to [18], a burning train stopping in a tunnel section, i.e. in the tunnel between portals and/or stations, is significantly less probable and, therefore, can be ignored with respect to maintaining tenable air conditions for escape. This is based on the assumptions that passive measures such as sidewalks, emergency exits and escape possibilities at a maximum walking distance of 300 m, etc. are provided according to German guideline BoStrab [6]. If these egress conditions according to [6] are not provided and upon engineering analysis, ventilation or other measures shall be provided in the tunnel in order to compensate for the adverse egress conditions.

Fires in stations are generally significantly more relevant than the possibility of burning trains stopped in a tunnel. This is supported by the following arguments:

- Stations are much better suited for evacuation of a large number of passengers and the application of a smoke control philosophy is much better suited for the finite environment of the station.
- The procedures among rail and metro operators always dictate for the train to continue out of the tunnel or into the nearest station should a fire or other incidents occur.
- Most metro or rail trains will not stop in the tunnel even if the emergency brake button is activated. The reason for not stopping in the tunnel is that a train stranded in a tunnel section raises issues like the long evacuation times of escaping from the coaches on the narrow and poorly illuminated walkways and the difficulties of applying the right smoke control strategy.

This guideline mainly focuses on rail systems providing short escape distances and wide egress path from the tunnel to a safe area according to [6], i.e. urban passenger rail systems without freight trains and/or dangerous goods. Thus, the probability of trains on fire reaching the next station is high and means for safe self-rescue are provided.

The approach of omitting scenarios with burning trains stopped in a tunnel section differs from the American norm NFPA 130 or others (see [11], [13], [14]). In [11] it is stated, for example, that any tunnel section with a length of more than 305 m shall be provided with a mechanical emergency ventilation system.

7.2 ANALYSIS OF FIRE AND SMOKE PROPAGATION

7.2.1 Approaches

The major approaches for analysing fire and smoke propagation are:

- One-dimensional (1D) approaches, where the aero- and thermodynamic parameters only depend on time and on axial location along the tunnel.
- Three-dimensional (3D) approaches (CFD = Computational Fluid Dynamics), where all relevant parameters are investigated as a function of time and of the three spatial coordinates.

In most cases a combined approach provides the best results for investigating fires in rail tunnels:

- 1D investigation of the whole tunnel system, where the appropriate boundary conditions (i.e. barometric pressure at the portals and wind loads) can be applied.
- 3D in-depth analysis of the fire zone, using the initial and boundary conditions (e.g. velocity distribution) resulting from the previous step.

This approach allows concentration of detailed 3D analysis (which is computationally much more demanding) on the fire zone, where detailed results are needed, while simplifying the analysis of the whole tunnel, where only global effects are relevant.

7.2.2 Scenario development

For the scenario of a train fire in a station, a realistic sequence of events needs to be defined including the following major time steps:

- Start of fire on train,
- Detection of fire by sensors, staff or passengers,
- Confirmation of alarm,
- Start of fire-fighting systems,
- Start of ventilation measures (active, passive),
- Arrival of train at station,
- Start of self-rescue phase from train and platform,
- Start of aided-rescue phase at arrival of rescue and fire service,
- End of aided-rescue phase.

7.2.3 Specification of a design fire

For the analysis of the escape and rescue conditions, it is essential that a design fire is defined. The temporal evolution of the release rate of heat, soot, gases, etc. is required as a source term for the simulation of the propagation of smoke, visibility, temperature and other properties in a station or tunnel.

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Fire characteristics cannot be defined in a general manner. In fact, due to the many influencing factors, fires with similar initial conditions might show quite substantial differences depending on stochastic influences. For example, in a fire test of a vehicle, windows may break at an early or late stage of the fire, depending on the exact fire location. This may lead to very different oxygen supply and growth rate of the fire. Additionally, vehicles of different age and type might show significantly different behaviour. Therefore, one single “standard design fire” for all different types of trains is not appropriate but classes of design fire need to be specified. In addition, a design fire should be considered as representative only.

Any real fire is likely to deviate from the design assumptions. At the moment, there is no accepted database listing the standard fire characteristics of different vehicle types for typical conditions in an underground system. An overview of current know-how for vehicle tunnels is given in [19]. Large-scale fire tests of sufficient quality are expensive. Theoretical analysis of fire characteristics or small-scale testing will leave major uncertainties. In spite of the difficulties, creating such a data base would reduce the currently existing wide range of different assumptions for design fires substantially and it would be quite beneficial for harmonising the design of different projects. The establishment of a database for design fires to fulfil engineering purposes is strongly recommended but outside of the scope of this guideline. In the following some general guidance will be provided.

An overview of typical fire loads is provided in Table 7.

Table 7: Design fires [24] (HRR = Heat-Release Rate)

	HRR MW	Road, examples vehicles	Rail, examples vehicles	Metro, examples vehicles	At the fire boundary
Risk to life	5	1-2 cars			ISO 834
	10	Small van, 2-3 cars, ++	Electric locomotive	Low combustible passengers carriage	ISO 834
	20	Big van, public bus, multiple vehicles		Normal combustible passengers carriage	ISO 834
	30	Bus, empty HGV	Passengers carriage	Two Carriages	ISO 834
	50	Combustibles load on truck	Open freight wagons with lorries	Multiple carriages (more than two)	ISO 834
	70	HGV load with combustibles (approx. 4 tonne)			HC
	100	HGV (average)			HC
	150	Loaded with easy comb. HGV (approx. 10 tons)			RWS
Risk to construction	200 or higher	Limited by oxygen, petrol tanker, multiple HGVs	Limited by oxygen		RWS

It is important to distinguish between accidental fire sources and fires caused by arson. With modern, fire-resistant rolling stock, only the latter is likely to generate fires with a high or very high heat-release rate. This is illustrated qualitatively in the following picture.

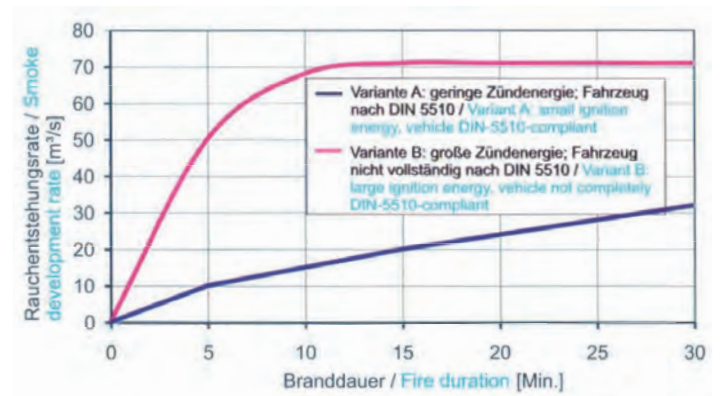


Figure 6: The influence of ignition energy on fire development [17]

As a general guidance for large fires, the following characteristics shown Figure 7 can be assumed. Specific engineering analysis is required for determining the fire characteristics where this parameter is critical. This is mostly the case whenever fires with a train stopped in a tunnel are accounted for.

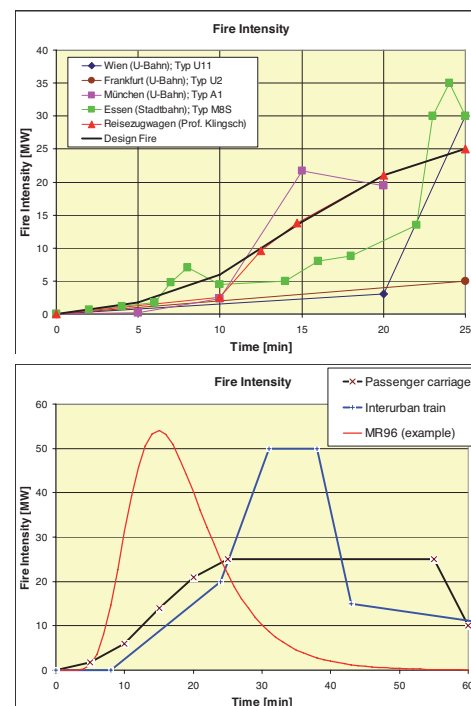


Figure 7: Fire curves (Germany).

Top: Various design fire curves for different mass transit cars in Germany; Bottom: Design fires for passenger carriage and interurban train (Deutsche Bahn) [21]. The curve “MR96” illustrates as an example a fire curve used for a specific train in a recent design project, computed based on [23].

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7.2.4 Sample results

The following images show typical images resulting from the simulation of fire scenarios in rail tunnels.

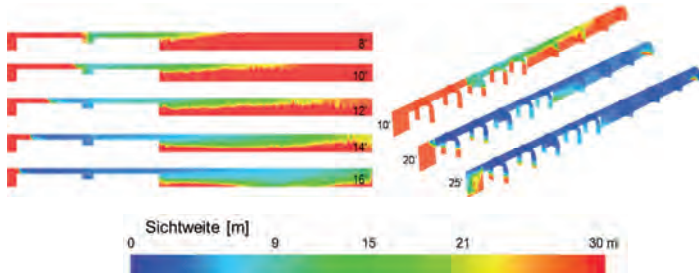


Figure 8: Visibility length with a 10 MW fire in the central part of a train with flow 1 m/s from left to right (longitudinal sections along the tunnel axis)

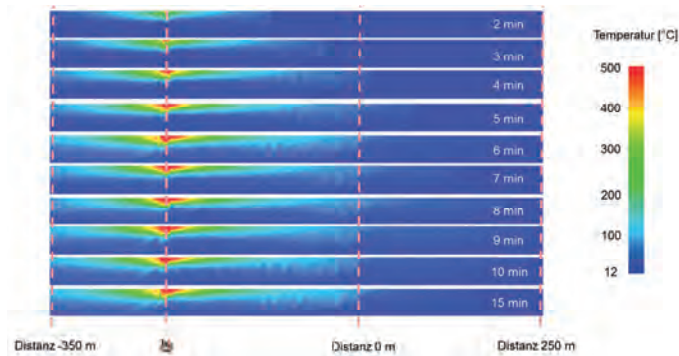


Figure 9: Time development of temperature with a 30 MW fire (longitudinal sections along the tunnel axis)

7.3 ANALYSIS OF EVACUATION PROCESS

7.3.1 Approaches

The major approaches for analysing the evacuation process are:

- Engineering analysis based on e.g. NFPA 130 [11].
- Detailed analysis using specific evacuation-simulation software.

While the former approach can be carried out in a very rapid and simple manner, detailed simulation is essential for all comparatively complex underground configurations.

The principal objective is to provide a tenable environment in the station for the phase of self-rescue. This requires calculating the period of self-rescue, which is required to move all staff and

passengers to a safe place. In this respect, it is recommended to follow at first the methodology for calculating evacuation times as recommended, for example, in the NFPA 130 ([11]). Aspects such as station occupant load, train occupant load and evacuation times from trains and platforms are standardized in a sufficient manner. Further refinements can be introduced based on the needs.

7.3.2 Person load

In the case of a train stopped in a tunnel, the number of persons to be accounted for depends essentially on the train's characteristics. The influence of several train occupancy levels should be investigated.

In case of fire in stations the estimate of the person load must take into account also waiting persons and the presence of other trains. Two main approaches can be recommended:

- **NFPA 130** : This approach is based on the peak hourly traffic volume. The "occupant load" is established based on traffic forecasts or counts [11].
- **EBA** : This approach is based on the following explicit formula [10]:

$$P_{max} = n (P1 + P2) + P3$$

With:

n = number of rails at the platform considered

P1 = maximum number of sitting persons on longest train

P2 = maximum number of standing persons on longest train

P3 = 0.3 (P1 + P2).

The simple approach of EBA can be recommended if detailed traffic data are lacking.

7.3.3 Analytic first estimate

Based on a large number of evacuation simulations, a simple analytical expression was derived, that allows estimation of the evacuation time as a function of the variables emergency exit distance, train length, minimum of exit door width and walkway width, walking velocity and number of persons [21]:

$$T_{eva} = 0.7029 - \frac{P_{train}}{1.465 \cdot c} + 1.863 \cdot \frac{(L_{exits} - 0.5 \cdot L_{train})}{v} = 0.7029 - T_{wait} + 1.863 \cdot T_{walk} \quad (1)$$

$$c = \min(\text{exit door width [m]}, \text{walkway width [m]}) \cdot 1.365 [P / m^2] \cdot v [m / s] \quad (2)$$

With:

T_{eva}	Evacuation time [s]	v	Walking velocity [m/s]
P_{train}	Number of persons on the train [-]	c	Person capacity coefficient [P / s]
L_{train}	Train length [m]	T_{wait}	Waiting time scale [s]
L_{exits}	Emergency exits distance [m]	T_{walk}	Walking time scale [s]

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The aim while developing this simple correlation was not to calculate the evacuation time as accurately as possible, but rather to find a fast evaluation method allowing for rough but quick estimates applicable for a wide range of trains and tunnels. The difference between the estimated and computed evacuation times is presented in Figure 10. The standard deviation is 3.17 min and the average deviation 8%, which is comparable to the likely uncertainty of the simulated results. It can be concluded that the empirical correlation allows approximation of the evacuation times in a manner, which is probably sufficiently accurate and reliable for most preliminary estimates.

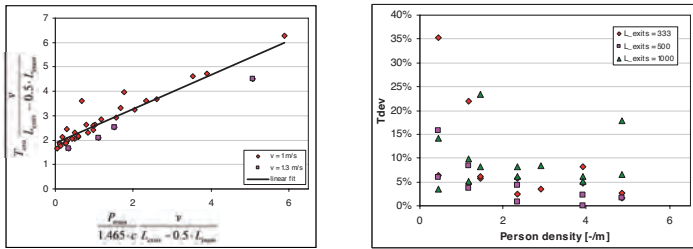


Figure 10 : Fit using all data (left) and relative deviation T_{dev} of predicted evacuation time (right)

7.3.4 Sample results

Sample results for the evacuation of a regional train after a stop in a tunnel are presented [21]. The train composition investigated consists of four coaches with a total length of 96 m. Up to three or four compositions can be coupled together for trains with a total length of 298 m or 394 m. A fully modelled version of this train (including seat benches, compartments, toilets, etc.), consisting of three compositions, was used for the investigations. Each coach has four doors (two on each side), measuring 1.32 m. The maximum capacity of 1'440 persons is considered (all seats are occupied and corridor is full of persons). The simulation was carried out using the commercial code ASERI.

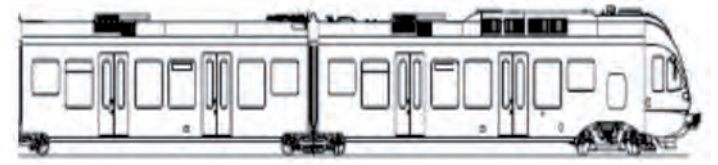


Figure 11 : Regional train (example)

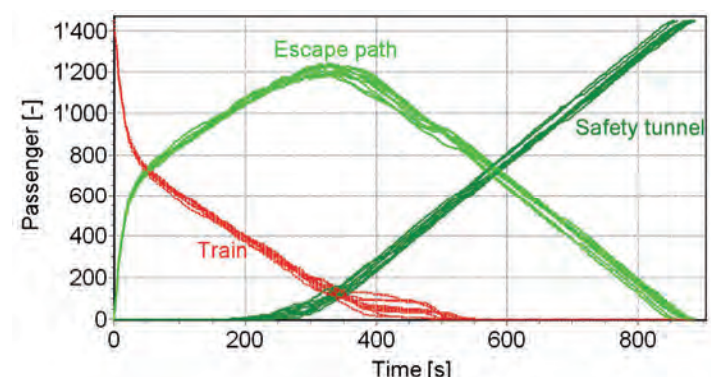
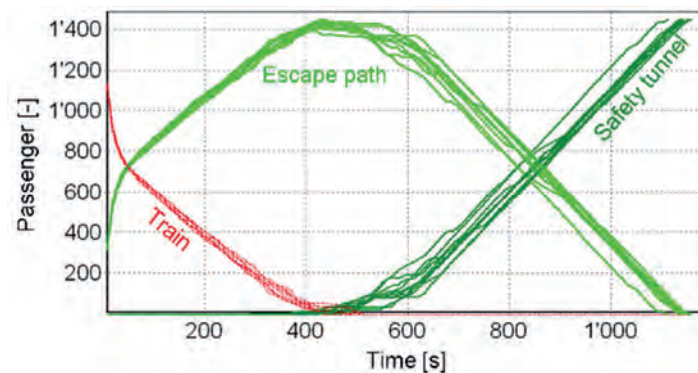


Figure 12 : Evolution of evacuation process for regional trains with high person load and emergency exit distances of 500 m (left) and 333 m (right)

