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Performance-based design of road tunnel fire safety: Proposal of new Swedish framework

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ABSTRACT

This paper contains a proposal of new Swedish framework for performance-based design of road tunnel fire safety derived from Swedish and European regulation. The overall purpose of the guideline is to protect life, health, property, environment, and key societal functions from fire. The guideline is structured into five key groups of requirements: #1 Proper management and organisation, #2 to limit the generation and spread of fire and smoke, #3 to provide means for safe self-evacuation, #4 to provide means and safety for the rescue service, and #5 to ensure load-bearing capacity of the construction. Each group contains a hybrid of prescriptive requirements, performance-based requirements, and acceptable solutions. Prescriptive requirements must be fulfilled, however, it is the choice of the design team to either adopt the proposed acceptable solutions, or to design alternative solutions by verifying that performance-based requirements are satisfied. For verification of performance-based requirements through risk analysis the operational, epistemic, and aleatory uncertainties are considerable. Therefore, a scenario-based risk analysis with several specified input variables and methods is recommended for verification of #3 and #5. Indispensable complements are scenario exercises, emergency exercises and similar methods that validate the design and highlight organisational aspects. The proposed design guide has been developed by the authors together with the advisory group established for the work.

Introduction

Catastrophic tunnel fires such as the Mont Blanc fire in 1999 have highlighted the potential consequences of such events. In the Mont Blanc case many people lost their lives, and the tunnel remained closed for several years [1]. In 2004 The European commission issued a directive on minimum safety requirements for tunnels in the trans-European road network [2].

Despite the directive and several national laws on tunnel safety, at large there is a lack of agreement regarding what constitutes tunnel safety and how verification of safety should be performed. Swedish stakeholders have a diversified view on this subject, it is to some degree unclear what constitutes fire safety, what an acceptable fire safety level should be and which roles different stakeholders have [3,4].

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According to the EC directive a risk analysis has to be performed, but it is not clear why or how the results should be used. In practice, due to several prescriptive requirements, there is a limited possibility for safety trade-offs. Furthermore, there is an imbalance, as most measures focus on reducing consequences instead of reducing the likelihood of occurrence. This is often due to predefined design fire requirements in which the fire has already been assumed to have happened, i.e. likelihood of occurrence is not emphasized. It was realised that future research should focus on developing the concept of acceptable performance and risk if we are to be able to consider safety trade-offs [4]. Therefore a project was initiated by the Swedish Transport Administration (STA) with the goal to develop performance-based fire safety guidelines. The purpose of this paper is to present a concept for more performance-based guidelines which would allow for risk-based design and for safety trade-offs, e.g., technical trade-offs between fire suppression and fire resistance.

The general idea of the new tunnel guideline was to resemble the procedure from the building regulation. By doing so it is hoped that the building industry will be familiar with the structure and procedure.

Legal requirements and political objectives

Several legal requirements and political objectives influence how a tunnel is designed and therefore also what requirements the tunnel must fulfil. The overall requirement for Swedish road infrastructure is to ensure a socio-economic efficient and sustainable provision of transport for citizens and industry throughout the country. Keywords are availability, safety, environment and health [5]. On a legal level the planning and building act [6] and the planning and building ordinance [7] applies to tunnels as they are construction works. In this ordinance five basic fire safety requirements for structures can be identified from the EU Construction Products Directive (CPD). For tunnels the act on safety in road tunnels [8] and the ordinance on safety in road tunnels [9] further specify the requirements set out in the EC directive. Other laws concerning crisis management [10,11], fire safety management [12,13], and the prevention of accidents [14] also sets requirements for the performance of tunnel fire safety. Specific requirements for buildings are issued by the Swedish National Board of Housing [15].

The Swedish building code

The current building code is, compared to previous editions, updated and re-written to better provide the designer with performance-based regulations and general recommendations supporting the requirements. As not all requirements can be formulated in a performance-based manner some prescriptive requirements still exist. The code separates the requirements from the recommendations which in turn provide guidelines for how the requirements can be fulfilled. The level of safety is then defined by the use of the general recommendations but they are not mandatory and other solutions to the requirements may be obtained by performance-based methods which fulfils the requirements, but not the general recommendations. The designer has to follow all prescriptive requirements.

The Swedish National Board of Housing, Building and planning [16] also issued guidelines for the verification method for performance-based solutions (known as the analytical design option). This guideline provides the designer with a recommended procedure for how to verify that the building meets the requirements. The guideline also includes information on practical design issues. The most frequently used formal base for the verification is the scenario-based risk analysis. The designer can apply other higher order methods like a quantitative risk analysis but also more qualitative methods. However, for these latter methods there are no detailed recommendations presented apart from the general procedures on performance-based design.

The performance-based procedure in the guideline presents a four step approach that has to be followed.

- Identification of the verification needs.
- Verification of a sufficient fire safety level.
- Review of the verification.
- Documentation of the fire safety measures in the building (including the performed control).

An important part of the procedure is the first two steps. The first step is used to identify the boundary conditions for the analysis and dependencies within the fire safety system. The second step includes a risk identification task aiming at identifying potential scenarios that are relevant for further analysis. There are no explicitly given scenario locations for each building type but the risk identification is supposed to provide the designer with a proper baseline for the ensuing verifications.

Theoretical framework for safe design

Performance-based design has become more common in several areas, for example within the building industry. In order to implement performance-based requirements for tunnels, functional requirements must be specified specifying the function and purpose of the tunnel from a fire safety perspective.

Treatment of uncertainty

Uncertainty is a fundamental phenomenon reflecting incomplete knowledge. Three types of uncertainty can be identified from literature to highlight different aspects. Aleatory uncertainty represents randomness, i.e. natural variations in samples. Epistemic uncertainty concerns the knowledge base and how well any model being used represents the real phenomenon [17]. Operational uncertainty is due to errors and assumptions being made by the analyst group and explain variations found in benchmarking exercises on risk analysis despite that the same data, theory and methods were used [18].

According to Morgan and Henrion [17] empirical quantities representing properties or states of the world can be represented by probability distributions. Epistemic and model uncertainties are in principle very difficult to capture in numerical terms, and since they do not represent real states of the world, it does not make sense to express them with probability distributions. Uncertainty can also be expressed in other ways, for example in words by stating the knowledge base and assumptions being made, or by a parametric sensitivity analysis.

Uncertainty can be treated in different ways and to a different extent. Depending on the problem context, available data and resources, a suitable level of uncertainty treatment can be aimed for. Paté-Cornell (1996) proposes six different levels in relation to risk analysis.

Level 0: Hazard detection and failure modes identification. We know what can happen, this might be sufficient for a strict zero-risk policy.

- Level 1: Worst case approach. This can be an option if the worst case is sufficient to support a decision, but it can be difficult to determine what 'worst' is.
- Level 2: Plausible worst case. This can be an option if we want to know a reasonable and plausible upper bound, however, it can be difficult to decide how plausible a certain case is.
- Level 3: Best estimates and central value. This reflects the most probable outcome and is often used for Cost and Benefit Analysis (CBA). Since nothing is said about the uncertainty involved it is impossible to predict likely fluctuations.
- Level 4: Probabilistic risk assessment, single risk curve. An output in terms of a probabilistic curve which displays the uncertainty involved under the limitations of used method and made assumptions).
- Level 5: Probabilistic risk analysis, multiple curves. This option takes into consideration of competing models and assumptions.

It will not be possible to categorize all methods according to the levels above, however for risk analysis the categorization is meaningful.

What is safety, and how can it be achieved?

Achieving a safe tunnel covers several different aspects. This is understood through the safety circle which visualize safety in different sequential stages [19] as a dynamic process of learning and improving, see Fig. 1. It has no beginning and no end. In any holistic safety work all elements in the safety circle should be addressed, it may be inefficient to only focus on one or a few measures. Pro-action is about eliminating the root causes, for example through training or design. Prevention is about reducing tunnel accident probabilities, for example through reduced speed. Preparation is about handling emergencies. Mitigation is about mitigating the consequences of a tunnel accident. Intervention comes from the efforts of rescue teams. After-care is about taking actions to return to normal operation. Lastly evaluation is about learning and improving. Safety features that function early in the circle are in general most cost-effective [19].

Another important aspect when it comes to safety is the fact that most accidents are caused or worsened by organisational factors [20–22]. Reason [20] classify human error into two groups: latent errors and active errors. Active errors are often performed by front-line operators and are noticeable as soon as they take place. Latent errors, however, are often performed by agents removed in time and space from the front-line operators, e.g. designers, high-level decision makers, and maintenance staff. Both active error and latent error are unavoidable, but there is still hope as we can identify them early and act upon them to continually ensure safety [20]. There are three key realms to improve safety as follows [20,23,24].

- Methods such as total quality management provide a framework for improving and finding latent conditions.
- Administrative controls: External controls are made up of rules, regulations, and procedures. Internal controls are derived from training and experience. Ideally combinations of administrative controls confine the natural variability of human action to safe and productive pathways.
- Engineering principles and methods for safe design: Inherent safety, fail-safe, safety margins, procedural safe-guards, systems engineering, risk analysis, etc.

Note that the proposed design guide is an administrative and external control, however, it should encourage several aspects from the sections above in order for safety to be ensured.

Fig. 1. The safety circle visualizes different aspects that contribute to safety.

Risk analysis as means for verification for road tunnel life safety

The two most common risk analysis methods for road tunnels are characterized by PIARC [25] as scenario-based and system-based. A scenario-based approach is qualitative in the way that one or more scenarios are selected upon experience, knowledge or regulation. It may be either quantitative or qualitative in terms of analysing the outcome of the selected scenarios. A system-based approach is a quantitative and probabilistic model, referred to as a Quantitative Risk Analysis (QRA).

In the Scenario-based approach, a limited set of scenarios is defined. The consequences for each scenario are evaluated against pre-defined criteria. The frequencies only play a role in the selection of the scenarios. This approach is well suited for analysis of particular events or planning of emergency response measures. This approach treats uncertainties according to Paté-Cornell's level 1, 2, or 3 depending on which scenario or scenarios that are chosen and their likelihood.

Unlike the scenario-based approach where a few scenarios are chosen, in a QRA all scenarios are considered. Both causes for incidents and system failures and analysis of the consequences are included in the analysis. Usually this is done through utilizing fault trees and event trees. A QRA correspond to Paté-Cornell's level 4.

Note, however, that not all requirements and systems can be verified by risk analysis. Risk analysis requires data and causal connections to be known for it to be meaningful, e.g. for many administrative and organisational safety measures the causal connections to end consequences are not well known, despite that the measures are known to be effective [20,26].

General requirements and guideline structure

Based on legal requirements, political goals, and latest research, requirements for tunnel fire safety are identified. An account of this work process is given in the final report of the project [27,28]. The hierarchy and structure of the resulting guideline can be seen in Fig. 2.

The guideline starts from the overarching aim to protect life, health, property, environment, and key societal functions from fire. Several requirements exist, mainly derived from laws, to fulfil this aim. The guideline starts with an introduction and general requirements. A key general requirement is that the fire safety protection is robust so that all or a large part of the protection does not fail by a common cause.

On a high level a safety concept is established for all tunnels, this is a description of key principles and technical, organisational, and administrative measures used to achieve safety. The safety concept is an overarching document presenting the strategy for safety of the tunnel.

All tunnels are divided into three classes (TA, TB, and TC) depending on traffic volume, amount of heavy goods, and tunnel length. Secondly there is an additional class (TA∗, TB∗, TC∗) for vulnerable tunnels with special need for protection. A tunnel can be vulnerable as a whole or concerning one or more specific requirements. For such cases the prescriptive solutions can in some cases be increased, or they are judged to be obsolete. Verification against performance-based requirements is then recommended.

Design and verification of compliance can either be performed by a simplified verification against pre-specified acceptable solutions, or by performance-based design. Performance-based verification follow the same procedure as is used for buildings, see "The Swedish building code". Depending on the complexity of the needed verification, the method can either

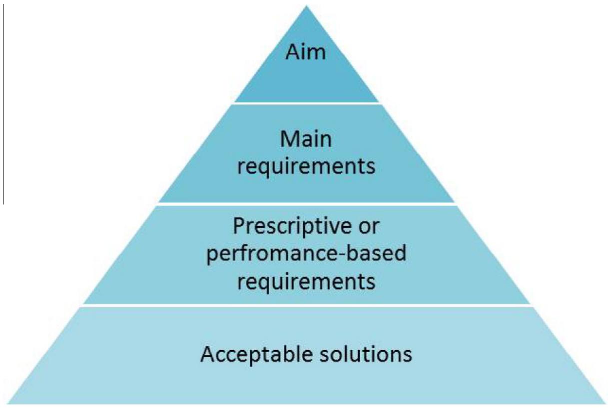

Fig. 2. Overview of the guideline structure.

be a qualitative analysis, scenario risk analysis, QRA, or another suitable method. Note that the suggested methods for performance-based verification are recommendations and that other methods may be used. The only requirement is that the analysis follows the procedure outlined in "The Swedish building code", and that performance-based requirements are fulfilled.

The fire protection is said to be satisfied if one of the following points are met:

- compliance with all requirements of the guidance,
- comparison with a reference tunnel with the resulting protection from applicable acceptable solutions showing equivalent or higher safety, or
- the criteria given in this guidance for scenario risk analysis are achieved.

After the general requirements the guideline is further structured into six groups of requirements which are as follows: organisation & management, to limit the generation and spread of fire and smoke, to provide means for safe evacuation, to provide means and safety for the rescue service, to ensure load-bearing capacity of the construction, and to limit the spread of fire to neighbouring construction works, see Fig. 3. Each group contains a hybrid of requirements consisting of prescriptive requirements, performance-based requirements, and acceptable solutions.

Main requirements and the performance of tunnel fire safety

From the derived guideline containing all specification for fire safety which is appended in the final report [27], the most important performance-based requirements can be identified. Group number six, limit the spread of fire to neighbouring construction works, only apply to very specific tunnels where nearby constructions exist and where these would be at risk. However, the other five groups of requirements are of significant importance for the overall performance.

Depending on the chosen safety concept, different systems can become critical for the overall safety. The safety concept will therefore affect, and to some extent, define the requirements for such systems (e.g. ventilation, fixed fire suppression systems, evacuation, or load-bearing capacity).

Organisation and management

As part of the ever on-going systematic fire safety work, the tunnel manager should ensure necessary organisational, administrative and technical measures for safe operation, proper maintenance, and efficient incident and traffic management. Training, learning and scenario exercises (tabletop exercises used to practise and evaluate alarm and decision chains) should be performed to validate and verify that the response to incidents, accidents and emergencies is efficient.

For vulnerable tunnels, exercises and other methods should ensure that the organisation that is created before, during and after crisis is fit to take appropriate response.

Almost every system is dependent on maintenance and the correct training to be functioning in the intended way when needed. Organisation and management is largely pro-active which in general makes it very cost efficient and effective albeit it may be hard to quantitatively assess its utility [26,28].

Verification of compliance could be internal and external administrative control [20] including the execution of exercises and existence of a total quality management (TQM) system such as ISO 9000 [29]. Through training and scenario exercise the organisation and technical requirements can be logically tested. In the Netherlands, several interesting methods are being used and developed in this respect [30,31]. Depending on the tunnel class up to three categories of exercises are proposed.

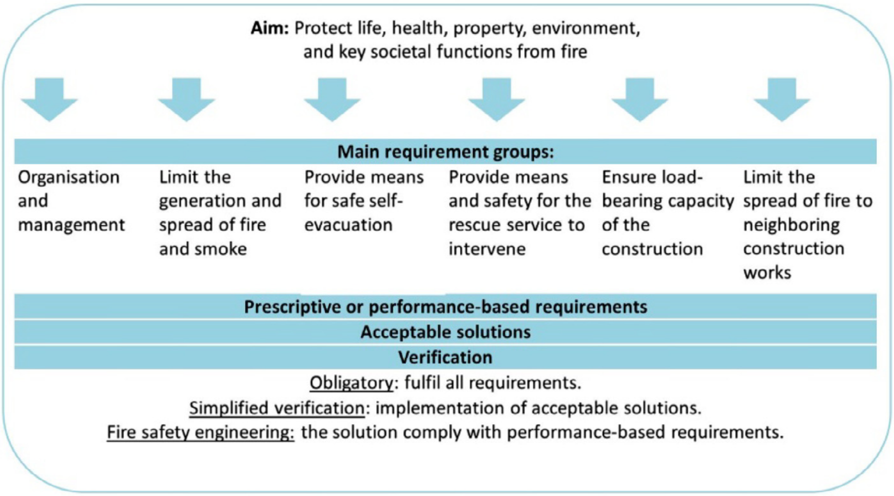

Fig. 3. Summary over the tunnel fire safety guideline.

To continuously improve safety during the operation of the tunnel the TQM system is essential to structure and drive this process.

Limit the generation and spread of fire and smoke

The main requirement of this section is to offer protection against the origin, development, and spread of fire and smoke within the structure. It can be subdivided in four subsystems: fire compartmentation, wall-lining material, ventilation, and fixed fire suppression systems (FFFS). Performance-based design methods may be applied or acceptable solutions may be adopted. Fire compartmentation and wall-lining material are best verified through standards, e.g. the Eurocode. This ensures that a fire will not spread or grow with the aid of the wall-lining material, and key structures such as escape route will endure a certain minimal time.

Fire compartmentation for tunnels primarily aims at protecting life (the spread of fire to other parts of the tunnel is not as severe as the fact that there already is a fire in the tunnel). EI 60 is recommended as a sensible level of protection in the light of the dynamics of a tunnel fire. Tunnel fires can be more severe than the ISO 834 standard fire curve (higher temperatures in the ceiling), but the dynamics of a tunnel fire follows the air flow along the tunnel which means the fire stress and the integrity of wall or doors at a height up to 3 m should not be more severely stressed than a corresponding one hour standard fire.

Depending on other requirements and the overall safety concept of the tunnel certain strategies for the ventilation system might be necessary to achieve a safe evacuation. Regarding spread and generation of fire a minimal amount of ventilation is preferable [32–34]. For limiting the generation and spread of fires a FFFS can be very effective [35]. This can also have a positive effect on other objectives such as evacuation, load-bearing capacity, and the rescue service as the fire, in general, will be smaller.

To provide means for evacuation

The tunnel shall offer the users the possibility to reach a place of safety in the event of an emergency. Evacuees must not be exposed to falling objects or physical obstructions, high temperature, high heat flux, high levels of toxic gases, or poor visibility. Verification of compliance can either be through the use of acceptable solutions or through performance-based design.

Evacuation is a difficult area which not only depends on the fire development and technical systems, but also human factors. In tunnel fires, smoke is what cause fatalities. Life safety is therefore best achieved if evacuation through smoke can be avoided (this could be a principle defined in the safety concept). Depending on the tunnel and traffic situation this could for example be achieved in unidirectional tunnels by ensuring that the smoke travels with the traffic flow and that downstream traffic safely can continue driving. Other tools for improving the smoke conditions in the tunnel can be a FFFS or a one or two-point smoke extraction system [36]. Thus, the need for verification depends on the safety concept and tunnel (e.g. evacuation in smoke can theoretically be avoided for unidirectional tunnels without traffic congestion with longitudinal ventilation >3 m/s). For the cases when evacuation has to be performed downstream a tunnel tenable conditions for the evacuees needs to be ensured. This can be achieved by complying with proposed solutions, or through performance-based design.

In the guideline, performance-based design through scenario-based risk analysis is proposed. For such an analysis there are many aspects that need to be thoroughly considered, for more details consult the guideline report [27]. As the scenarios are pre-specified, this sets the level of safety to strive for. To account for the fact that some tunnels bear a higher risk, the risk classes defined earlier are used to differentiate. Likely fires for tunnels involving single vehicles are a car fire, an HGV fire, or a bus fire. A relatively large HGV fire (50–100 MW) can be seen as a worst plausible fire. This fire is selected to test the system for the case when all systems work as intended. This means that if for example an FFFS is installed, the benefits from this can be accounted for. However, to account for the risk that safety systems may not work as intended, and to aim for a robust solution, a plausible fire in a car (5–10 MW) is used to stress test the system when one safety system is out of order. To ensure safety also for vulnerable tunnels, e.g. tunnels under water, more difficult scenarios are used for the stress test. To account for the influence from ventilation on the fire size, the fire can be reduced or increased if the ventilation is higher or lower than 3 m/s. In Table 1 the fire scenarios for the evaluation of life safety are given.

To provide means and safety for rescue operations

The main requirement is that the rescue service can undertake life-saving and fire extinguishing activities with satisfactorily safety for their personnel. A rescue plan must be drawn up in conjunction with the local rescue service. Furthermore it must be possible to locate the position of fire, to reach the fire, to have means for controlling the smoke and extinguishment, and to be able to communicate by radio in the tunnel. To ensure the safety of rescue personnel several measures can be taken: a ventilation system can control the heat and smoke, FFFS can reduce the fire size and cool the fire and structure, and the load-bearing capacity should be in relation to their need. This requirement can be verified and developed through scenario exercises, training or by other means.

To ensure load-bearing capacity of the construction

The final key performance parameter is the load-bearing capacity. The main goal with this requirement is that the load-bearing capacity of the construction can be assumed during the event of fire. A collapse or partial collapse could lead to time consuming reparations or refurbishments which, from a socio-economic perspective can be very expensive. This was not least the case with Mont Blanc after the fire in 1999 the tunnel remained closed for three years. In the developed guideline two methods are proposed to verify that the load-bearing capacity is sufficient. The first method is based on a time-temperature curve which the design should handle for a specified amount of time. Choosing between standardised fire curves, the HC-curve defined in EN 1991-1-2 was selected. However, tunnel fires can be more severe than the HC-curve why the RWS curve sometimes is proposed [27]. At the other extreme the ISO 834 standard curve is sometimes used for tunnels although it underestimates the ceiling temperature considerable. A drawback with the RWS curve is that it has such fast temperature increase that the material values of Eurocode do not apply. A second important design fire parameter is the length of fire exposure. Vehicles involved in a tunnel fire are likely to burn intensively for less than one hour [37], however, during this time the ceiling temperature can be as high as 1350 °C. In the design guide we have proposed to use the HC-curve. To account for differences in tunnel risks, longer time periods are proposed for tunnels with a higher risk, see Table 2 below. However, to use a pre-specified fire curve is a crude approach as neither the tunnel cross-section, ventilation, tunnel fire dynamics, or any FFFS are considered. Therefore, a more performance-based approach is also suggested.

In the performance-based approach the ceiling temperature is calculated from a set of representative scenarios for the load-bearing capacity. In the calculation method, originally proposed by Li and Ingason [38], parameters such as ventilation, fire size, and tunnel geometry are accounted for. This will lead to a unique time-temperature curve for the specific tunnel in question. Scenarios for evaluation of the performance-based design are, as for verification of life safety, pre-specified, see Table 3.

In Table 4 below the key performance parameters are summarised in terms of performance criteria, method for verification, the purpose and effect on other systems.

Table 1
Proposed fire scenarios for performance-based verification of life safety.

Scenario group	Heat release rate	Fire growth	Yields and heat of combustion
1	A goods vehicle fire TA: 100 MW TB: 75 MW TC: 50 MW	TA and TB: $\alpha = 0.19$ kW/s^2. For tunnels with longitudinal air flow less than 1.5 m/s: $\alpha = 0.047$ kW/s^2 TC: $\alpha = 0.047$ kW/s^2	$Y_{CO2} = 2.5$ g/g, $Y_{CO} = 0.1$ g/g, $Y_{Sot} = 0.1$ g/g, $Y_{HCN} = 0.01$ g/g $H_{ec} = 25$ MJ/kg
2	A car fire TA: 10 MW TB: 7.5 MW TC: 5 MW	All tunnel classes: $\alpha = 0.047$ kW/s^2	

Table 2
Proposed fire scenarios for verification of sufficient load-bearing capacity.

Tunnel class	Not sensitive to collapse[a]	Sensitive to collapse[a]
TA	120 minutes, HC-curve	180 minutes, HC-curve
TB	90 minutes, HC-curve	180 minutes, HC-curve
TC	60 minutes, HC-curve	180 minutes, HC-curve

[a] A collapse-sensitive tunnel is one that passes underneath a water body, or which would create serious consequential effects in the event of a collapse, or where there are buildings above the tunnel.

Table 3
Proposed fire scenarios for verification of sufficient load-bearing capacity.

Scenario group	Not sensitive to collapse[a]	Sensitive to collapse[a]
1	100 MW and 500 GJ goods vehicle fire, $\alpha = 0.19$ kW/s^2	100 MW and 1000 GJ goods vehicle fire, $\alpha = 0.19$ kW/s^2
2	10 MW and 20 GJ car fire, $\alpha = 0.047$ kW/s^2	100 MW and 500 GJ goods vehicle fire, $\alpha = 0.19$ kW/s^2

[a] A collapse-sensitive tunnel is one that passes underneath a water body, or which would create serious consequential effects in the event of a collapse, or where there are buildings above the tunnel.

Table 4
The key performance requirements that make up tunnel fire safety.

Requirement	Suggested method for verification	Performance	Purpose and effect on other requirements
1. Organisation & Management	Internal and external administrative controls, planning, training, scenario and emergency exercises, TQM system	Efficient handling of different sets of scenarios depending on tunnel class	Almost all tunnel functions depend on this requirement. It should therefore have the highest priority
2.1 Fire compartmentation	Standard/testing	EI 60 or E 30 with FFSS (ISO 834)	Primarily ensure safe escape route and safe functioning of safety systems
2.2 Wall-lining material	Standard/testing	Eurocode classes, see report [27]	Should not ignite easily or contribute to fire spread
2.3 Ventilation (not necessarily a requirement)	Overall safety concept to evaluate the need, International standards and simulation for system verification	*Prescriptive:* acceptable solution 100 (20) MW fire for longitudinal (transverse) system. *Performance-based design:* aiming at fulfilling requirements for which ventilation is necessary.	Support evacuation and rescue service. Ventilation can increase the risk for fire spread
2.4 FFFS	Simulation/testing/calculations	Depending on purpose	Cool the fire, surfaces and fire fumes. Improves the conditions for generation and spread of fire and smoke, load-bearing capacity, evacuation and rescue service
3. Provide means for evacuation	*Prescriptive verification:* acceptable solutions, or *Performance-based verification:* Scenario-based risk analysis (or other suitable method)	*Prescriptive:* compliance with acceptable solutions, or *Scenario-based risk analysis:* Tenable conditions for evacuation for applicable scenarios, see Table 1	Tunnel users should be able to safely evacuate the tunnel without being exposed to untenable conditions
4. Provide means and safety for the rescue service	Prescriptive requirements in tandem with training, scenario and emergency exercises	Efficient and safe handling of different scenarios	Saving life, property and environment in the event of accidents, taking account of the risks for the rescue personnel
5 Ensure load-bearing capacity of the construction	Prescriptive verification: Testing or inquiry, or Performance-based verification: Scenario-based risk analysis (or other suitable method)	*Prescriptive:* Ensure load-bearing capacity for the fixed time-temperature curve, see Table 2. *Scenario-based risk analysis:* Load-bearing capacity ensured for selected scenarios, see Table 3	Prevent collapse and large socio-economic consequences, enable evacuation and rescue service intervention

Discussion

The advantage with performance-based design is that specific solutions appropriate for the actual circumstances can be engineered. However, the disadvantage is that verification is more difficult. In contrast a prescriptive approach is easier to verify and is usually based on practice from what has worked before, which means that it is robust for standard application, but may be a poor solution under new circumstances.

Another difference between the two approaches for verification is that technical changes or coupling effects between safety systems aiming at different main requirements can be accounted for in a performance-based approach. For example, if FFFS is installed in the tunnel it affects several other parameters such as the fire size which might result in a prescriptive solution becoming obsolete or unnecessary conservative.

Some requirements in the guideline are still more prescriptive than performance-based, this is most often due to that there are prescriptive legal requirements which need to be fulfilled and/or because no clear and verifiable performance-based requirements could be formulated. However, another solution which often has been applied is that prescriptive legal requirements are made into recommended acceptable solutions and a parallel performance-based requirement. In legal terms this should be satisfactory as the European directive on tunnel safety [2], as well as some Swedish laws, opens up for alternative solutions provided that the alternative measures will result in equivalent or improved protection, i.e. if the performance-based requirement is satisfactorily met. One interesting example is ventilation which is regulated in several paragraphs in the EC directive although, in terms of performance-based thinking, ventilation is just a means to reach several other goals. Therefore the EC requirements on ventilation are turned into a recommendation of an acceptable solution, while several performance-based requirements, e.g. means for evacuation, decide the requirements for ventilation in a performance-based solution.

In relation to the safety circle, all but the requirement on organisation and management deal with preparation, mitigation, and intervention. This likely has to do with the current paradigm being consequence-focused, as was noticed in the pre-study [4]. If current laws are used as guiding principles the result will focus on the same thing as the laws. On the other hand, organisation and management covers all aspects of the safety circle but mitigation.

From a legal perspective and from the tradition in Sweden there is little encouragement in using other engineering methods than risk analysis for achieving safety (e.g. fail-safe design, inherent safety, or Systems Engineering). Based on reference group meetings and interviews it also seems that there is much room for improvement of TQM systems and administrative controls [28]. As a consequence we often speak about ‘verification of safety’, however for performance-based design one should also consider validation. Verification in engineering commonly refers to “are you building it right?”, while validation refers to the question “are you building the right thing?” Systems engineering, for example, is one field that systematically deals with these two issues. However, Scenario exercises, and emergency exercises are two methods from the guideline that highlight the issue of validation, even if different exercises in reality can give results related also to verification. Scenario exercise can be used early in the design to highlight different essential functions and needs. Emergency exercises can be carried out once the design is ready and validate the final installations and overall organisation.

The sometimes recommended method for performance-based verification, scenario-based risk analysis, is in Paté-Cornell’s classification either a level 1, 2, or 3 analysis in relation to how uncertainties are treated. There are many different models available for tunnel risk analysis at level 4 which, at the moment are being in the development or maturing phase [39], why the expected outcome can differ by several orders of magnitude [25,40]. Below follows a discussion of the reason for these uncertainties and its implication for the choice of method.

For tunnel risk analysis epistemic, aleatory and operational uncertainty can be expected to be large. The epistemic uncertainty is large as large tunnel fires happen very seldom. Furthermore, old data may not fit to new tunnels. The epistemic uncertainty is large as the theory and models on fire development, human behaviour and structural stability is limited. Fire modelling started to be developed in the 1970’s and is now widely used in fire sciences. However, a round-robin study in 2007 on an enclosure fire where ten teams simulated the same fire given the same information shows disappointing result. The time to flash-over varied from no flashover to 850 s where the real time was 300 s. The maximum smoke layer temperature varied between 211 °C and 1170 °C where the real temperature was 750 °C. The HRR curve from the ten teams looks like a scatter plot between 1 MW and 10 MW. As the HRR curve determines many other parameters, the prediction of any parameter varies significantly. Their conclusion is that there is an inherent difficulty in predicting fire dynamics [41]. As tunnels differ from buildings in several respects and are less researched we can expect even larger uncertainties.

The first response, from the 18th century, to understanding human behaviour in fire was simply to label it as panic; an irrational behaviour involving the breakdown of group ties and acts on self-preservations at all costs. Another naive approach is what is often called the physical science model, in which humans are simplified to rational dots starting to move to the nearest exit as soon as the fire alarm sounds. As a response to these two approaches, starting from the late 1960’s, several less naive models for describing human behaviour have been developed, e.g. [42–45]. However, computer models for fire evacuation are still at the level of the physical science model which is a very simplistic way of modelling human behaviour in fires [46,47].

The operational uncertainty is high as a result of the lack of precision and knowledge arising from the two sections above. Therefore, many critical assumptions has to be made and as a result the uncertainty in risk estimates is large [25,40]. An important category of accidents involving multiple vehicles is particularly bound with uncertainties at the present [25]. This is problematic as this is the type of accident that historically have caused several fatalities [48]. Furthermore, in terms of consequences, prediction of fatalities and injuries is difficult, as is modelling of human behaviour, exposure and effect on humans. Despite these uncertainties, many countries use system-based approaches, for example The Netherlands, Austria, Switzerland and Norway [25,40].

From the paragraphs above, some reasons for recommending a scenario-based risk analysis can be identified as follows. As the scenarios are pre-specified in the guideline the epistemic uncertainty from estimating the likelihood of fire size is removed from the operation of the analyst. Concerning the verification of load-bearing capacity a method derived from experimental data for calculating the resulting time-temperature exposure is proposed by the design guide, this means that the uncertainty from various fire modelling activities is reduced. Concerning the verification of life safety the yields for various toxic substances are specified which means that simpler models may be used and the operational uncertainty and assumptions are reduced. Several recommendations are given concerning what factors to account for when human behaviour is modelled although no specific model or formula is specified. That no model or formula is specified for human behaviour is probably the greatest source of operational and epistemic uncertainty of the proposed performance-based design guide.

Conclusions

A Swedish framework for a performance-based design guide for tunnels has been proposed. The framework is presented in detail in the report [27]. The framework allows for both prescriptive and performance-based design depending on the need. From the framework eight key performance parameters are identified.

The idea of the tunnel guideline and Swedish building regulation is to let the designer choose which verification principle to use for each affected requirement. In the regulation this is achieved by presenting performance-based requirements together with acceptable solutions as recommendations. This means that one can either choose to implement the acceptable solution(s) to automatically fulfil the requirement, or one could engineer another solution using performance-based design to verify that the performance-based requirement is achieved. The advantage compared with current, more prescriptive, framework is that more efficient solutions taking account of actual risks and needs can be engineered.

For verification of performance-based requirements through risk analysis there are considerable operational, epistemic, and aleatory uncertainties. By aiming at the simpler risk analysis methods, e.g. scenario-based risk analysis, and by offering guidance or fixed values on several input variables it is argued that some of the operational and epistemic uncertainties are reduced. Other methods, e.g. scenario exercise, STAMP and emergency exercises, addressing validation and organisational factors are an indispensable compliment.

The vision for further studies is to develop the design process, and from a socio-economic and quality perspective balance, or optimize, possible safety measures.

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