



Requirements and verification methods of tunnel safety and design

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Abstract

The report explores the foundations for a sound approach to performance-based fire safety design in tunnels. The main reason for conducting this study is that Swedish stakeholders have different opinion about what constitutes tunnel fire safety. Two main issues are discussed here, namely specification and verification of fire safety. Literature was reviewed and some international tunnel safety experts were interviewed. Tunnel fire safety can be specified through a combination of the: aim of fire safety, objectives and functional requirements, a set of scenarios to handle, and prescriptive requirements. Tunnel fire safety can be verified through several existing tools. Examples of these tools are scenario analysis, quantitative risk analysis, engineering tools to structure and systemize the process, and through using safety oriented procedures. It is important to consider safety in all stages of a tunnel: planning, design, construction and operation. To achieve this, effort needs to be invested in the process to clearly structure it and access it more easily. Relevant stakeholders need to be included wherever they are present and decisions continuously need to be verified and validated in later stages of the design process.

Key words: Tunnel fire safety, performance-based design

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Contents

Abstract	2
Contents	3
Preface	6
Summary	7
Sammanfattning	9
Abbreviations	11
1 Introduction	12
1.1 Background	12
1.2 Swedish requirements specific for tunnels	13
1.3 Purpose of this report	15
1.4 Limitations	15
1.5 Disposition	15
2 Ensuring satisfactory fire safety	16
2.1 Fire safety in tunnels	16
2.1.1 The tunnel-vehicle-human system	17
2.1.1.1 Functional requirements of the tunnel-vehicle-human system	17
2.2 Integrated approach to tunnel safety	18
2.2.1 Safety level criteria	20
2.3 Categorization of methods for verification according to the treatment of uncertainty	21
2.3.1 Uncertainty	21
2.3.2 Six levels of uncertainty	22
2.4 Risk analysis for road tunnels	22
2.4.1 Scenario-based approach	23
2.4.1.1 Dutch example of a scenario-based approach for road tunnels	23
2.4.1.2 French Scenario-based approach for verification of safety	24
2.4.2 System-based approach (QRA)	24
2.4.3 Evaluation	25
2.4.4 Recommendations for the practical use of risk analysis	25
2.4.5 Further analysis and recommendations for the use of risk analysis	25
2.5 Verification and evaluation of risk and safety	26
2.5.1 Technical risk evaluation and risk criteria	26
2.5.2 Economical risk evaluation	27
2.5.3 Societal and ethical risk evaluation	27
2.5.4 Risk framing	27
2.5.5 General (mixed) theory for risk evaluation	28
2.5.6 UK practice of Tolerability and acceptability	29
2.5.7 Drawbacks and delimitations of the HSE framework	29
2.5.8 Risk evaluation principles and guidance in Sweden	30
2.5.9 Choice of risk measure	32
2.5.10 The importance of defining the problem and of how it is defined	32
2.6 Acceptable risk	33

3	Fire safety regulation	35
3.1	International Maritime Organization (IMO)	35
3.2	NFPA 101 Life Safety Code 2009 Edition	37
3.3	NFPA 502	37
3.4	Verifying building works fire safety in Sweden	38
4	Evaluation and exploration of tunnel safety systems	40
4.1	How can a tunnel safety system be evaluated?	40
4.1.1	Prescriptive verification	40
4.1.2	Fire safety engineering	40
4.1.2.1	Systemic, quantitative risk analysis (QRA)	40
4.1.2.2	Scenario analysis	40
4.1.2.2.1	Design fire	41
4.1.2.2.2	Egress analysis	41
4.1.2.3	Failure analysis	41
4.1.2.4	Cost Benefit analysis (CBA)	41
4.1.3	According to the safety circle	42
4.1.4	Context, costs and benefits	42
4.2	Tunnel safety functions or systems	42
4.2.1	Organisation	42
4.2.2	Reliability and redundancy	42
4.2.3	Traffic and incident management	43
4.2.4	Fire prevention	44
4.2.5	Fire detection and monitoring equipment	44
4.2.6	Fire fighting	45
4.2.7	Evacuation and risk to life	45
4.2.8	Structural safety	46
4.3	Summary of safety systems, their importance and the possibility of evaluation	46
5	Experience from other countries	50
5.1	Australia	50
5.1.1	Peter Johnson and Paul Williams, ARUP	50
5.1.1.1	Burnley tunnel fire	51
5.1.2	Shan Raffel, Queensland Fire and Rescue Service	51
5.1.3	Nick Agnew, Stacey Agnew Pty Ltd	52
5.2	The Netherlands	53
5.2.1	Thijs Ruland and Twan Daverveld, Royal Haskoning	53
5.2.1.1	Functional approach to tunnel safety	53
5.2.1.2	Scenario analysis	54
5.2.1.3	Integrated functional design approach	54
5.2.2	Ronald Mante et al., Rijkswaterstaat (RWS)	55
5.2.2.1	Systems engineering design process	56
5.2.2.2	Specifications	56
5.2.2.3	Verification and validation (V-model)	56
5.2.2.4	Failure definitions	58
5.2.2.5	Critical safety functions	59
5.2.2.6	RWS QRA model	59
5.2.2.7	Scenario analysis	60
5.2.2.8	New approach	60
5.3	Georg Mayer, PTV, Germany	60
6	Discussion	62
6.1	Discussion and limitation of the interviews	62
6.2	Foundations for a new tunnel standard	63

7	Conclusions	66
8	References	67

Preface

In a preparatory study Ingason et al. (2009) found that there is a lack of agreement between Swedish stakeholders concerning tunnel safety and that the design document General Technical Description for Road Tunnels, ATB Tunnel 2004 is too rigid.

This document has been replaced in 2011 but the new document has in general the same type of requirements. This project was initiated by Mr Bernt Freiholtz at the Swedish Transport Administration to address this lack of agreement. The aim of this report is to present an updated background description for the concise recommendations that will be given in the final project report. The report gives general background information for the development of fire safety requirements for road tunnels.

The project has been financed by the Swedish Transport Administration. The project group and authors of the report consist of Haukur Ingason, SP, Anders Lönnermark, SP, Håkan Frantzich, Lund University, and Jonatan Gehandler, SP. The project participants would like to thank Bernt Freiholtz, the project coordinator, in particular together with the other members of the advisory group who have contributed to the project.

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Summary

In Sweden there is no uniform view of fire safety in tunnels. It is to some degree unclear what constitutes fire safety, what an acceptable fire safety level should be and which roles different stakeholders have. This report aims at presenting approaches on how fire safety is specified and verified internationally today.

Report objectives

The intention of this report is to explore the foundations for a future Swedish design standard specifying fire safety requirements for road tunnels. The objective is to investigate how fire safety in tunnels can be measured, what level is satisfactory, and how fire safety can be verified.

Fire safety for road tunnels

Fire safety for tunnels (or safety in general) is captured by three concepts from PIARC:

- (a) the safety circle describing different types of safety measure in a time-sequential manner: for example pro-active and preventive measures to reduce the amount of accidents, preparation, mitigation and intervention to reduce the consequences as much as possible, after-care to re-open the tunnel as fast as possible and lastly evaluation to learn and improve.
- (b) The bow tie model which looks at accidents in two ways: events leading to an incident, and events following an initial incident leading to end consequences, and
- (c) the integrated approach to safety that includes many different, but connected areas are as follows.
 - Safety level criteria specifying desired level of safety.
 - Infrastructure safety measures involving the technical systems and instruments, geometrical and structural solutions and materials used in all parts of the tunnel.
 - Operational safety measures including procedures for adequate tunnel safety management.
 - Socio-economic and cost-benefit criteria: how to do the trade-off between safety and cost effectiveness.
 - Safety assessment for verification of tunnel safety .
 - Knowledge of road tunnel usage: re-asses safety, should the traffic flow or characterisation change more than previewed.
 - Stage of the tunnel life affecting the detail of a safety analysis.
 - The use of operating experience.
 - Tunnel condition: ensure the intended function.

Scenarios for fire safety in tunnels, e.g. stopped vehicle, crash, fire, represent an end functional requirement of what the tunnel system should provide. The scenarios are preferably chosen by relevant stakeholders. During the design stage a scenario analysis can be used to evaluate the proposed design. At later stages, table top emergency exercises involving key emergency stakeholders organize the incident management and emergency response. Similar approaches are used by several countries, e.g. The Netherlands, France and Australia. Finally the process, from planning and design to operation, needs to be tailor-made so that relevant stakeholder are included and decisions continuously are validated and verified.

Safety level criteria

Deciding what is an appropriate, acceptable or tolerable level of safety is primarily an ethical and political issue. Such a decision will always be subjective and will thereby be based on judgements, there is no universal level of “acceptance”. Furthermore such a decision is highly dependent on available resources and the level of safety on the overall network.

Tunnel safety systems and the evaluation of their benefit

Followed by a literature review, systems used or recommended for tunnel safety are listed. The next step was to investigate on what terms each system can be evaluated, i.e., through prescriptive requirements, system-based risk analysis, scenario-based risk analysis, failure analysis, or a CBA. It is clear that no method fits all systems. This should be considered if requirements are to be verified on an advanced level, e.g., only specifying criteria in terms of risk curves. This means in practice, that not all systems can actually be evaluated. Therefore, more than one criterion must be used in order to capture the diversity of safety.

Fire safety regulation

Fire safety standards and regulations from numerous countries, organisations and fields are compiled. For performance-based design it is important that top and sub objectives are clearly stated and that methods for verification are described. Top objectives reveal the real purpose and aim of the whole regulation. Prescriptive rules should still be an option and implicitly they describe an implied acceptable level of safety.

Experience from other countries

From the interviews with tunnel safety professionals from three other countries and the literature review it was found that.

- Specification of scenarios is efficient both for validation and verification. It has also shown to be a good communication tool which helps create an efficient emergency organization and plan.
- The Netherlands was found to use many interesting novel techniques for verifying tunnel safety derived from large organizations and standards worldwide.
- The process is as important as the final design.

Sammanfattning

I Sverige finns idag ingen enhetlig syn på tunnelsäkerhet. Det finns olika uppfattningar kring vad som utgör tunnelsäkerhet, vad som är en acceptabel nivå, samt vilka roller inblandade aktörer har. Rapporten syftar till att presentera lösningar av hur tunnelbrandsäkerhet mäts och verifieras internationellt idag.

Syfte och avgränsningar

Rapporten syftar till att utgöra grundmaterial för formuleringen av en framtida svensk målstandard för brandsäkerhet i tunnlar. Det betyder mer konkret att utreda hur brandsäkerhet kan mätas, vilken nivå som är tillräcklig samt hur den kan verifieras.

Brandsäkerhet i vägtunnlar

PIARC presenterar tre perspektiv som åskådliggör säkerhet i allmänhet, dessa är den så kallade "bow-tie"-modellen, säkerhetscirkeln samt PIARC:s ramverk för ett integrerat angreppssätt.

- (a) I bow-tie modellen belyses ett tidssekventiellt tänkande där varje incident förutsätter ett antal faktorer som leder fram till incidenten. Vidare beskriver den ett antal följande händelser som är förknippade med olika konsekvenser.
- (b) Säkerhetscirkeln beskriver säkerhetsarbetet sett ur ett större perspektiv och inkluderar även delar som belyser vikten av att dra lärdom av tidigare incidenter.
- (c) Slutligen så täcker PIARC:s ramverk för tunnelsäkerhet följande aspekter.
 - Kriterier för nivå av säkerhet.
 - Tekniska system och utformning.
 - Operativa åtgärder (procedurer och organisation).
 - Ekonomiska aspekter ur ett livscykelperspektiv.
 - Verifieringsanalys.
 - Kunskap kring användandet av tunneln.
 - Tunnels olika livscykler.
 - Erfarenheter från driften.
 - Tunnelns faktiska funktion.

Att specificera scenarier som tunneln skall hantera ger en tydlig och funktionell bild av vad tunnelsystemet i slutändan ska klara av. Inblandade parter väljer ut representativa scenarier som skiljer sig från normal drift. Under projekteringen kan scenarioanalys användas för att evaluera designalternativ. Innan tunneln tas i drift kan scenariospel användas för att organisera hanteringen av incidenter och olyckor. Liknande metoder används bland annat i Holland, Frankrike och Australien. Slutligen bör hela processen, från förstudie till byggplan och drift skräddarsys så att relevanta parter medverkar och beslut kontinuerligt verifieras och valideras.

Säkerhetsnivå

Frågan gällande vad som utgör en acceptabel nivå av säkerhet är av politisk och etisk natur. Ett sådant beslut kommer alltid att vara normativt och inkludera värderingar. Ett sådant beslut beror även till stor del av tillgängliga resurser och säkerhetsnivån på vägnätverket som helhet.

Tunnelsäkerhetssystem och dess utvärdering

Genom en litteraturstudie sammanställdes en tunnelsäkerhetssystem för brand. Dessa undersöktes sedan baserat på hur deras nytta med avseende på säkerhet kan utvärderas, dvs. genom preskriptiv verifiering, systembaserad riskanalys, scenariobaserad riskanalys, tillförlitlighetsanalys, och kostnad-nytta analys. Resultatet pekar på att ingen metod utvärderar alla system. Detta är av stor vikt när en tunnel kravställs eftersom krav behöver formuleras på olika sätt för olika verifieringsmetoder, att till exempel bara formulera ett krav i form av en riskkurva betyder att inte alla system i praktiken utvärderas.

Lagar, föreskrifter och standarder för brandsäkerhet

Lagar, föreskrifter och standarder för brandsäkerhet sammanställs från ett antal olika länder, organisationer och branscher. En viktig lärdom är att om funktionsbaserade lösningar ska vara fruktsamma måste regelverket vara välstrukturerat med tydligt formulerade mål, funktionskrav och metod(er) för verifiering. Preskriptiva regler bör fortfarande vara en valmöjlighet samtidigt som dessa implicit beskriver en godtagbar säkerhetsnivå.

Erfarenhet från andra länder

Från litteraturstudien och efter intervjuer med nyckelpersoner i Holland, Australien och Tyskland kan bland annat följande konstateras att.

- Specificering av scenarier är effektivt både för verifiering och för validering. Att använda scenarier har även visat sig vara bra i kommunikationen mellan aktörer inblandade i olyckshanteringen.
- Holland bedöms använda många intressanta metoder för verifiering och validering av säkerhet (t.ex. RAMS, SIL).
- Processen är minst lika viktig som den slutliga designen.

Abbreviations

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
ASET	Available Safe Egress Time
BLEVE	Boiling Liquid Expanding Vapour Explosion
CBA	Cost-Benefit-Analysis
CCTV	Closed-Circuit Television
DARTS	Durable and Reliable Tunnel Structures
DGQRAM	Dangerous Goods Quantitative Risk Analysis Model
DGV	Dangerous Goods Vehicle
FIT	Fires in Tunnels
FMEA	Failure Mode and Effect Analysis
FN-curve	Frequency Number curve
HGV	Heavy Goods Vehicle
IRCC	Inter-Jurisdictional Regulatory Collaboration Committee
IRGC	International Risk Governance Council
LNG	Liquefied Natural Gas
MW	Megawatt (energy)
PIARC	World Road Association
QRA	Quantitative Risk Analysis
RAMS	Reliability, Availability, Maintainability and Reliability
RSET	Required Safe Egress Time
RWS	Rijkswaterstaat (Dutch infrastructure administration)
SE	Systems Engineering
SIL	Safety indicator level
SMART	Specific, Measurable, Attainable, Relevant and Time-bound
STA	The Swedish Transport Administration
TOPAAS	Task Oriented Probability of Abnormalities Analysis for Software
ToR	Tolerability of Risk
Tunnel 2004	General Technical Description for Road Tunnels, ATB Tunnel 2004
UPTUN	Upgrading of existing Tunnels for fire safety
WP	Work Package

1 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 (Lacroix, 2001). In 2004 The European commission released the Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (EC, 2004). These minimum requirements and the national and international experience of tunnel operation and safety form the foundation of Swedish regulation for ensuring tunnel safety. Internationally, the World Road Association, PIARC, strives to create a world forum for tunnel safety knowledge.

Several Swedish laws affect the construction of a tunnel. These laws include prescriptive requirements but are overall quite vague and provide requirements on a general level. In Sweden, the Swedish Transport Administration (STA) or the City of Stockholm are mainly responsible for building and planning tunnels in Sweden. When a new tunnel is to be constructed it is necessary to specify what it is expected to handle, for example expressed as the number of vehicles per day. Therefore the Swedish Transport Administration (STA) have developed a general technical description for road tunnels, ATB Tunnel 2004 (Tunnel, 2004), which will be referred to as Tunnel 2004 in this report. Tunnel 2004 provides rather detailed specifications for the tunnel; but, as the guidelines are rather prescriptive, the STA wishes to replace Tunnel 2004 by a future performance based design standard. In the meantime STA has recently replaced Tunnel 2004 with an updated document; Tunnel 11, but the overall safety measures are similar to the previous document and Tunnel 2004 will, therefore, be referred to throughout.

In Sweden 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 (Boverket, 2005b). This report mainly aims at investigating how tunnel fire safety can be specified, expressed, and verified. It is a pre-requisite to include concerned stakeholders and to adopt a functional perspective. Swedish circumstances will be referred to but not investigated to any broad degree.

1.1 Background

In the preparatory study to this project the basis to why a future design standard is needed and how it can be synthesized was laid, see (Ingason et al., 2009). STA has raised concerns that Tunnel 2004 is too rigid and performance-based guidelines would allow for risk-based design and for safety trade-offs, e.g., technical trade-offs between fire suppression and fire resistance. Fire safety needs to be managed in a way that accounts both for the design and the operation of the tunnel. The vision for further studies is to develop the design process, and from a socio-economic and quality perspective balance risk analysis, safety systems and connections between the physical environment and human behaviour. Future studies should form the basis for performance-based requirements on fire safety.

Tunnel 2004 includes performance-based ideas. For example, it states that a risk analysis should be performed and there is also an overall criterion stating that safety in general should not be lower than on similar roads above ground¹. However, in reality every fire safety system discussed in the standard contains prescriptive requirements. Therefore, the result from a risk analysis does not really affect the final safety level. A risk analysis has to be performed, but it is not clear why or how the results should be used. There is a limited possibility for safety trade-offs. Today 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

¹ What form of safety is not further elaborated, for example it may also include health aspects. Another relevant question is if one fatality due to fire equal to one fatality due to traffic accident

assumed to have happened, i.e. likelihood of occurrence is not emphasized. In future research, it will be necessary to develop the concept of acceptable risk if we are to be able to consider safety trade-offs (Ingason et al., 2009).

Performance-based design has become more common in other areas, for example within the building industry. In order to implement performance-based requirement for tunnels, functional requirements must be designed specifying the function and purpose of the tunnel from a fire safety perspective. Within the building industry there have been reports about deficits in the verification of performance-based design (Lundin, 2001): non verified praxis, incomplete handling of uncertainties, and poor documentation. Experience shows that it is important that the requirements are verifiable and clear. Probably risk analysis needs to be reviewed during the design process. An attempt to remedy the described situation in Sweden includes new and clearer guidelines on methods for verifying safety (BBRAD1, 2011).

The overall requirement for Swedish road infrastructure is to ensure an efficient and sustainable socio-economic provision of transport for citizens and industry throughout the country. Keywords are availability, safety, environment and health (Trafikverket, 2011). It will be important to clarify the design conditions so that the five basic fire safety legal requirements for structures in the Planning and Building Ordinance (PBF) are fulfilled. These five legal requirements correspond, according to Cronsioe et al. (2010), to the EU Construction Products Directive (CPD):

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

- *The load-bearing capacity of the construction can be assumed for a specific period of time,*
- *The generation and spread of fire and smoke within the works are limited,*
- *The spread of fire to neighbouring construction works is limited,*
- *Occupants can leave the work or be rescued by other means,*
- *The safety of rescue teams is taken into consideration (Cronsioe et al., 2010).*

1.2 Swedish requirements specific for tunnels

The overarching regulations on safety in road tunnels originate from the EU directive 2004/54/EC on the minimum safety requirements for tunnels in the trans-European road network. This directive has been adopted in Swedish regulations in the Act on safety in road tunnels (SFS, 2006:418) and the following Ordinance on safety in road tunnels (SFS, 2006:421) further specifying the requirements. In addition, the Planning and Building Act (PBL, 2010:900) and Planning and Building Ordinance (PBF, 2011:338) specify general requirements on any building works including tunnels. These requirements are expressed in a general manner stating that the building works shall have safety measures in order to provide a sufficient safety level concerning life safety and prevention of fire spread and smoke spread within the building works. More specific requirements for buildings are issued by the Swedish National Board of Housing (Boverket, 2011a)

The road tunnel act and ordinance describe the requirements on the operation of the tunnel. The requirements are valid for all road tunnels longer than 500 m which is an expansion of the requirements from the EU directive which only specifies the requirements for such tunnels that are within the Trans-European Road Network.

At the lowest formal regulatory level The Swedish National Board of Housing, Building and Planning has issued mandatory provisions on safety in road tunnels (BVT1, 2007:11) These provisions are requirements further explaining the minimum level of safety in tunnels longer than 500 m. This document is on the same legal level as BBR19, presented in section 3.4.

STA, which is the main owner and operator for roads and road tunnels in Sweden also has to follow the instructions issued by the government. This means that STA has to work in accordance with the national plan for the transportation system 2010-2021. This plan, developed by three transportation agencies in Sweden (for land, air and sea transport), originates from the transport political goals defined by the government and which in turn have their origin in the national parliament environmental goal for 2020 concerning a sustainable environment for the next generation.

The transport political goals aim, for the whole country, to provide a secure socio-economically efficient and sustainable transportation system for people and industry. This overarching goal is complemented by two additional goals (Trafikverket, 2011).

- Performance goal: availability and accessibility.
- Consideration goal: safety, health and environment.

The performance goal implies that the design, function and use of the transportation system shall give everyone a basic accessibility with good quality and usability which contributes to the development of the country. The transportation system shall be gender neutral, i.e. equivalent regarding women's and men's transport needs.

The consideration goal implies that the transportation system's design, function and use must be adapted so that no fatalities or serious injuries occur, and such that it contributes to environmental quality goals are achieved and to better health.

The national plan for the transportation system is also influenced by a government proposition and directive having the following focal points:

- jobs and business,
- needs and climate adaption,
- road user needs and regional priorities, and
- socio-economic analyses shall be an important factor.

All these goals imply that a performance-based standard for tunnel safety regarding fire must be sustainable for a long time and provide a sufficient level of safety for the road users, including children, the elderly, people with disabilities and people with a different background.

In practical terms, the tunnel design team has to follow the guidelines provided in the formal regulations, for example the road tunnel act and ordinance and in the mandatory provisions on safety in road tunnels (BVT1). These provide both performance-based descriptions and more detailed regulations on issues relevant for tunnel fire safety. Defining a tunnel fire safety standard means that all detailed regulations must be fulfilled for example by providing escape routes in the tunnel at least every 150 m. This requirement cannot be handled in another way than meeting this prescriptive demand. There is of course a possibility to have shorter distances between the escape routes as a result of a formal safety assessment, such as a risk analysis.

On the other hand smoke spread to the escape routes shall be managed by the use of suitable installations such as doors, which is more like a performance-based requirement. There is, therefore, a possibility to use other means for preventing smoke spread to the escape routes than using doors or by using doors in combination with other installations. The key point is that there is an option for alternative solutions.

In a future design code it is, therefore, necessary to explicitly define the prescriptive regulations relevant for each tunnel and to provide guidelines for how to manage the other performance-based regulations by for example explaining the adjoining objectives.

1.3 Purpose of this report

The aim of the report is to investigate international safety practice and regulations in order to have a sound basis for future recommendations for a future Swedish design standard for fire safety in road tunnels. This means searching for answers to questions such as what constitutes tunnel safety? How can it be expressed or measured? What level of safety or risk is acceptable or tolerable? A sub objective is to present fire safety guidelines and requirements in a clear and easy manner.

A future design standard for Sweden should be more clear in terms of verifying satisfactory fire safety for all concerned parties than the existing standard. Furthermore, it is important to allow the possibility of performance-based design, while making the future design standard more functional.

1.4 Limitations

The report is about fire safety. However, as the objective is to include the frequency of fires as well as to take a holistic approach, the report cannot be limited only to the event fire, i.e., assuming that the fire has already happened. Therefore, all events that are reasonably likely to lead to a fire are included. From a design perspective, parameters being more related to traffic safety on roads in general, such as side lining, will not be included.

Compliance with Tunnel 2004 should imply that all laws regarding fire safety are fulfilled. At the same time societal and political values should be respected. The following boundary conditions govern the project and the future design standard:

- new findings from research and development,
- values present within society and the government today, and
- existing laws and regulations.

1.5 Disposition

In chapter two, three important questions are investigated: what constitutes tunnel fire safety and how can it be expressed, how can fire safety be verified, and what level is acceptable or tolerable? Thus chapter two is about different methods and perspectives to describe, analyse, and verify fire safety. Chapter three presents key Swedish and international fire safety regulations and standards. Chapter four investigates tunnel fire safety systems and functions from the perspective of how their use can be evaluated or measured. In chapter five practical experience and approaches to tunnel design and safety from Australia, The Netherlands, and Germany are presented. In chapter six the foundation for a future Swedish design standard is discussed. The report ends with conclusions in chapter 7.

2 Ensuring satisfactory fire safety

The objective is to answer the question concerning which criteria or requirements ensure satisfactory fire safety in tunnels. This has two main components: Firstly, what measures fire safety (methods and perspectives), and secondly what level is acceptable? This chapter describes means to ensure fire safety. The fire safety regulations are not included in this chapter, but are investigated in chapter 3.

2.1 Fire safety in tunnels

Fire safety in tunnels is about limiting the number of fires and limiting the consequences of a fire if it occurs. A fire may start in a driving vehicle, as a consequence of an accident, or due to malfunctioning tunnel equipment or vehicles. The two main end consequences are human life and economic impacts on society arising from infrastructure repair and disturbance in case of closure:

“Tunnels are important infrastructures which facilitate communication between extensive areas of the European Union (EU) and are therefore essential for long-distance transport and the development of regional economies. However, accidents in tunnels, and particularly fires, can have dramatic consequences and can prove extremely costly in terms of human life, increased congestion, pollution and repair costs” (EC, 2007).

In the EU Directive for minimum safety requirements the primary objective is the prevention of critical events that endanger human life, the environment and tunnel installations. The secondary objective is the reduction of possible consequences of events such as accidents and fires to enable people to rescue themselves, allow immediate intervention of road users, ensure efficient action by emergency services, protect the environment and limit material damage (EC, 2004). In the EU project Fire in Tunnels (FIT) the most important consequences were prioritized as follows (Anderberg et al., 2009).

1. Goals related to life safety:
 - a. minimize the risk to injury or death for tunnel users,
 - b. minimize the risk to injury or death for persons outside the tunnel, and
 - c. minimize the risk to injury or death for the emergency service or workers.
2. Goals related to economic consequences and quality of life:
 - a. avoid damages that threatens the stability of the structure reducing the utility of the tunnel,
 - b. avoid expensive repair costs, and
 - c. avoid long tunnel closure.

Four main factors are considered to influence the level of safety: infrastructure, operation, vehicles and road users (UPTUN, 2006). In the EU project Durable and Reliable Tunnel Structures (DARTS), hazards and consequences for tunnels were studied and analysed (DARTS, 2004). Including some basic events used in The Netherlands (Arbouw et al., 2006), the following critical events or hazards are identified:

- Dropped item.
- Stopped vehicle.
- Traffic congestion.
- Collision between vehicles.
- Collision with the tunnel structure.
- Fire.
- Fire spread.
- Explosion.
- Toxic and aggressive materials.

- Flooding.
- Earthquake.

Obviously events that may cause a fire need to be included since one of the objectives is to include the likelihood of occurrence. A dropped item may lead to a collision which, in turn, may initiate a fire. Traffic congestion may lead to a collision while at the same time making an evacuation more difficult. Therefore, the first five events must be considered. Obviously events starting with a fire are also within the scope of this analysis.

However the events: explosion, toxic and aggressive materials, flooding and earthquake will not be addressed as they are either very unlikely to happen in Sweden or because they are dealt with as separate cases through other standards and regulatory documents.

2.1.1 The tunnel-vehicle-human system

The desired scenario of the tunnel-vehicle-human system is that of a flow of vehicles driving at the speed limit with a safe distance between them. All drivers are alert and the traffic information system is easily interpreted and does not induce any further risks. All scenarios deviating from this scenario may pose a smaller or larger risk, not only for accidents. We must also focus on other events that reduce safety, and for each identify the risk and potential barriers. In the end, a group of barriers are selected for the design in order to fulfil the functional requirement that the human-vehicle-tunnel system is in control (Hollnagel, 1999, Hollnagel, 2006). The goal of the design should be the effective functioning of the human-vehicle-tunnel system as a whole (Hollnagel, 2006). The important question then is what is this function? How is it described? Perhaps something like: efficient and safe transport flow of the human-vehicle systems (through each tunnel system) in which the driver is at control? Basically, this is fairly close to the governmental goals of the road infrastructure system (Trafikverket, 2011). The next section looks at functional requirements that can be defined in terms of holistic effective functioning.

2.1.1.1 Functional requirements of the tunnel-vehicle-human system

From a tunnel-vehicle-human perspective some of the previously identified hazards can be used to describe what the tunnel should deliver, or handle. The following events are presented in order to achieve both high availability and a safe tunnel. Less severe events affect mainly traffic management and incident management while the more severe events affect emergency management and after-care. The ‘as planned’ scenario is included as well which is good practice in risk analysis (Kaplan, 1992). The tunnel organisation should therefore in terms of fire safety handle the following.

- The ‘as planned’ scenario: steady and safe flow of traffic, all safety equipment and function is well maintained and ready to be used.
- Degradation of safety equipment or function: the tunnel operator should know what to do and when the tunnel must be closed or when other measures should be taken to ensure safety. Reduce likelihood of occurrence through proper training and maintenance.
- Dropped item scenario: dropped item on the road, notify drivers and/or conduct the traffic around it. Remove it as soon as possible.
- Stopped vehicle: vehicle has stopped on the road or at the side of the road. Same action as above.
- Traffic congestion: Through traffic management the traffic can be conducted to limit congestion inside the tunnel. There should also be plans ready for alternative routes.
- Accident scenario (collision): Incident management and emergency response plan knows what to do. Reduce the risk through proper traffic management and incident management.

- Fire scenario: The purpose of this scenario is to reduce the consequences of fires. Stop entrance to the tunnel, facilitate self-rescue and extinguish the fire as early as possible. Restore tunnel to full operation status as fast as possible.

The purposes of these events or scenarios are not to be exclusive. They emphasise, however, what functionality the tunnel-vehicle-human system should have.

2.2 Integrated approach to tunnel safety

In the report ‘Integrated approach for tunnel safety’, PIARC (2007) developed by the world road association a framework for holistic road tunnel safety is presented. The overall safety objectives are:

1. *“Prevent critical events that may endanger human life, the environment and tunnel installations.*
2. *Reduce the consequences of accidents, such as fires by creating the prerequisites for:*
 - a. *people involved in the incident to rescue themselves:*
 - b. *road users to intervene immediately to prevent greater consequences:*
 - c. *ensuring efficient action by emergency services:*
 - d. *protecting the environment: and*
 - e. *limiting material damage (PIARC, 2007, p. 35).”*

Safety is seen through two paradigms: the safety circle, Figure 1, and the bow-tie model, Figure 2.

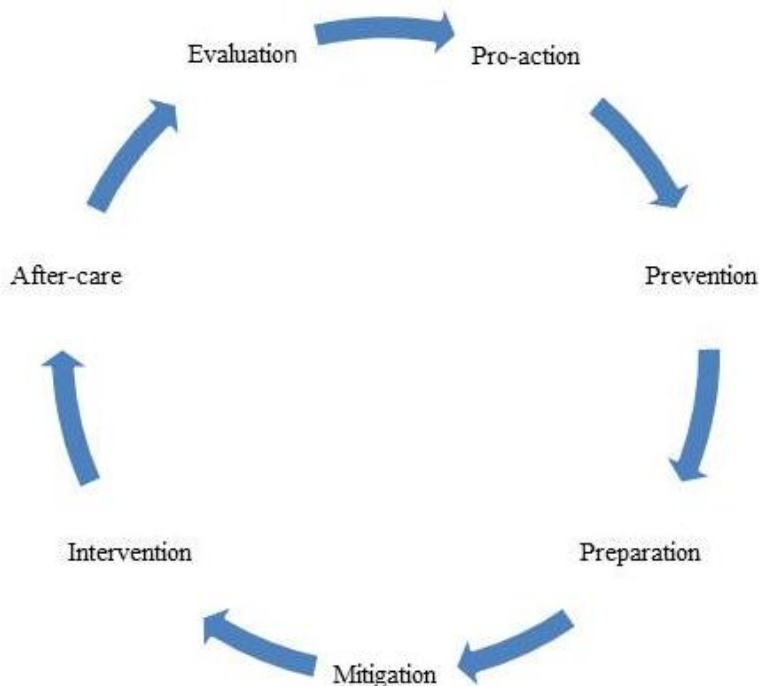


Figure 1 Safety Circle (PIARC, 2007)

In any holistic safety system all elements in the safety circle should be addressed. It may be inefficient to only focus on one or a few elements. 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. Safety features that function early in the circle are most cost-effective in general.

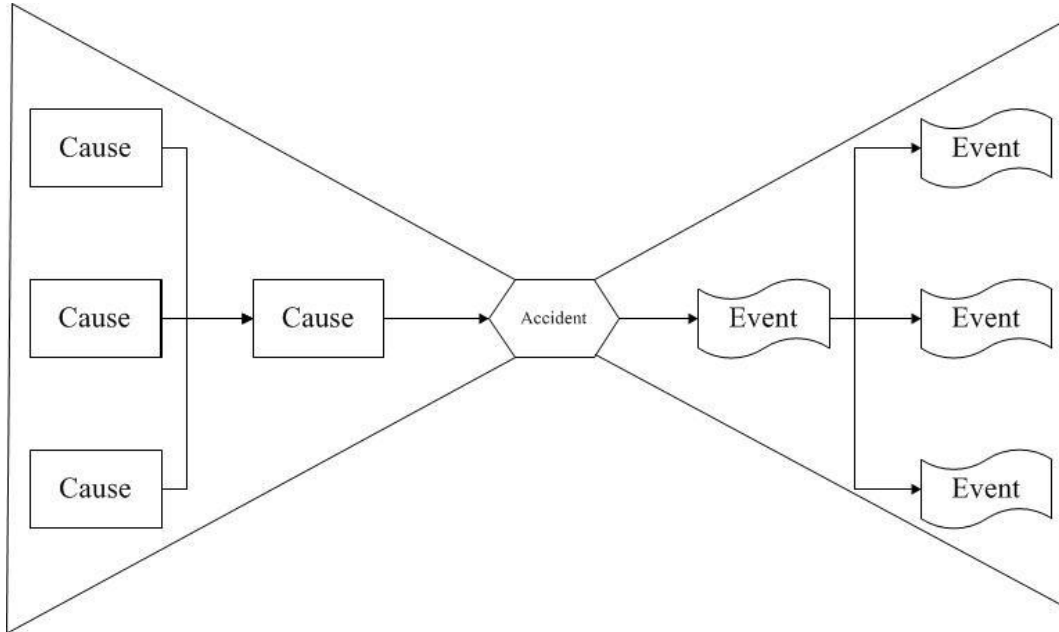


Figure 2 The bow tie model

In the bow tie model some core features from risk analysis are captured. The left tie represent causes leading to an incident, which in a risk analysis often are treated using a fault tree. The right tie contains the effects or consequences of the incident. This is often treated with an event tree in risk analysis. The bow tie model is sequential in time, from the left to the right. A structured bow-tie model makes it relatively easy to see how a certain risk influences the system and how different measures could be taken to decrease either the likelihood for or consequences of an event.

It may be worth noting that there are also other paradigms concerning representing or understanding incidents: In epidemiological models, in analogy with a disease, accidents may be the outcome of a complex combination of factors, some manifest and some latent, that happen to exist in space and time (Hollnagel, 2002). Instead of decomposing the system into smaller parts, the system can be viewed as a whole in which the actual functions of the system are studied through for example the use of chaos theory models. Obviously a sequential accident model will likely result in finding specific root causes. An epidemiological approach would identify carriers and latent conditions as indicators of system “health” and a model based on the bow-tie model would find conditions that from experience are associated with accidents.

The key elements in the framework for an integrated approach are:

- *“Safety level criteria.*
- *Infrastructure and operational measures.*
- *Socio-economic and cost-benefit criteria.*
- *Safety assessment techniques.*
- *Knowledge of road tunnel usage.*
- *Stage of the tunnel life.*
- *Using operating experience.*
- *Tunnel system conditions.” (PIARC, 2007, p. 49)*

Safety level criteria include one or more of the following items: minimum safety requirements and safety standards, safety processes involving all relevant stakeholders, safety standards or values for risk or safety or deterministic standards for relevant scenarios. Not all possible safety features are needed for every tunnel, only features needed to fulfil the safety criteria.

Infrastructure safety features involve the technical systems and instruments, geometrical and structural solutions and materials used in all parts of the tunnel. Operational safety features include procedures for adequate tunnel safety management. For example inspection, maintenance, and traffic management. Other aspects are co-ordination of the duties of operators, maintenance crew and rescue teams which should be well described and tested periodically, also including after-care and evaluation in the safety circle.

Socio-economic and cost-benefit criteria are about how to do the trade-off between high quality and reliability in terms of safety versus cost effectiveness. It is necessary to take a life cycle approach and to include also other factors such as the effect on the surrounding environment in order to understand the overall project value.

Safety or risk assessment is the common tool for verification of tunnel safety in several countries. The EU Directive for tunnel safety requests a risk analysis to be done. A Safety assessment answers the question of whether the desired level of safety has been reached. Safety assessments are by PIARC divided in two groups.

- Probabilistic safety assessment, which for example could be a Quantitative Risk Analysis (QRA). In the bow tie model both the right and left side are included. The aim is to evaluate both consequences and probabilities in a systematic and holistic manner.
- Deterministic safety assessment, which could be a scenario analysis. In the bow tie model only the right-hand side is considered explicitly (this could be complimented with a complimentary method focusing on the left hand side, for example Failure Mode and Effect Analysis (FMEA) or resilience engineering). The left hand side is implicitly considered in terms of the choice of scenarios.

PIARC recommends the safety to be re-assessed should the traffic flow or characterisation (road tunnel usage point above) change more than expected.

The stage of the tunnel life affects the detail of a safety analysis. After some time in operation, operating experience can contribute to further improving the safety and organisation.

The condition of the tunnel system determines the function. In order to assure the prescribed function, procedures for maintenance and inspection are needed. This includes assessing the degradation in safety given that the function is compromised and to take appropriate measures such as complementary measures or to close the tunnel.

The PIARC proposal for an integrated approach to safety highlights the different phases: planning, design, construction and operation. Safety analyses at different levels with different objectives depending on the phase are performed and the tunnel safety documentation and organisational preparedness is continually improved.

2.2.1 Safety level criteria

What is an acceptable risk can be expressed in a number of ways, either in qualitative, quantitative or semi-quantitative terms. It is important that the overall measures are a good representation of the fire safety, and that there are trustworthy and sensible methods for calculating the measures. Any measure can have a criterion specifying the acceptable level of safety. In the EU project Upgrading of existing Tunnels for fire safety (UPTUN)

work packages (WP) 2 and 5, criteria for safety are suggested. In WP 2 The following performance-based criteria for life safety were suggested (Ingason, 2005):

- visibility > 10 m,
- gas temperature < 60 °C,
- radiation < 2 kW/m², and
- toxic gases FI < 1 (model by Purser).

In WP 5 (UPTUN, 2006) safety level criteria from a holistic perspective were suggested. This includes:

- allowable risk in terms of societal and individual risk criteria,
- tunnel safety manager who is responsible for incident, contingency, disaster and maintenance plans,
- performance-based safety requirements:
 - **prevention:** Avoid traffic congestion, obstacles/disturbances and other potential accident causes,
 - **correction:** Mitigate the consequences,
 - **self-rescue:** Enable tunnel users to reach a safe place, and
 - **repression:** Provide information to the emergency services.

2.3 Categorization of methods for verification according to the treatment of uncertainty

As is pointed out several times in this report (see e.g. section 2.2, 5.1.1 and 5.2.2), the design process is important. It is important to verify and validate both the design process: are we building the right thing, and are we building it right? Further, concerning the end result, before opening the tunnel, is it safe enough? Verification of the process is mainly discussed in chapter 5. The remainder of this section will focus on verification of the end result, the final tunnel design.

In order to categorize methods used for verification, such as scenario analysis or QRA, the framework of Paté-Cornell will briefly be presented. Paté-Cornell (1996) defines six different levels of treatment depending on the level of treatment of uncertainty in risk analysis.

2.3.1 Uncertainty

Uncertainty is an ambiguous concept with many different definitions being used, which is why it need to be clarified. In this report uncertainty will be seen as a fundamental phenomenon reflecting incomplete knowledge. Unlike in, for example, decision theory where one can make a decision under certainty, the current concept of uncertainty means that there will always be uncertainty because our knowledge about future events is, in practice, never complete. Uncertainty can be due to randomness (aleatory), representing variations in samples. It can also be concerning the knowledge base, when the evidence base is small (epistemic).

It can furthermore be related to the model being used, how well it represents what one is actually trying to model. Probability is often used to represent uncertainty. For example a probability distribution could represent the uncertainty in a certain parameter. Then one could argue that one can be uncertain about the shape of the distribution curve.

Morgan and Henrion argue that only empirical quantities representing properties or states of the world should be represented by probability distributions (Morgan and Henrion, 1990). 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.

2.3.2 Six levels of uncertainty

The six levels proposed by Paté-Cornell (1996) are expressed in terms of different risk analysis approaches. However, uncertainty is always present so whatever method is being used it is of great value to describe the treatment of uncertainty. The six levels are as follows.

- **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.

These six levels are dependent on the available knowledge and statistics. In some cases it does not make sense to perform an analysis on level 5 because there may not be any numerical models or data available. Uncertainty can also be treated for example in words by stating the gaps in knowledge, or through reducing the uncertainty in the system by making it more robust. It will not be possible to categorize all qualitative analysis according to the levels above. A word of caution is needed, however, in terms of tunnel risk assessment there are many different models available (at level 4) which, at the moment are being in the development or maturing phase (Apostolakis, 2004), and the expected outcome can differ by several orders of magnitude (Ferkl and Dix, 2011, PIARC, 2008).

2.4 Risk analysis for road tunnels

Methods for verifying safety can according to (Beard and Cope, 2007) be characterised as either one or a combination of the following.

- Verification of compliance to prescriptive rules.
- Qualitative models (based upon knowledge, experience or systematic qualitative analysis such as FMEA).
- Quantitative models.
 - Physical models or experimental tests.
 - Theoretical models.
 - Deterministic.
 - Prediction of given variables (for example Newton’s law).
 - Non-deterministic.
 - Probabilistic models (prediction of outcomes).
 - Statistical models (no concept of probability).
 - Point schemes (heuristic: a way of distilling expert knowledge).

The two most common risk analysis methods for road tunnels are characterized by PIARC as scenario-based or system-based. A scenario-based approach is qualitative in the way 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 falls into the category of a quantitative, non-deterministic probabilistic model, and will be referred to as a Quantitative Risk Analysis (QRA).

A holistic approach to risk analysis, studies the interactions between the road users, operators, vehicles and infrastructure. This is wishful thinking based on the ideal case and in reality models are not perfect. The objective of a risk analysis is to be proactive, to predict future events; however, due to lack of data and imperfect models the prediction will be more or less accurate. The procedure of a risk analysis contains the following basic steps: definition of the system, hazard identification, likelihood analysis, consequence analysis, risk estimation, and evaluation (PIARC, 2008).

2.4.1 Scenario-based approach

In the Scenario-based approach, a limited set of relevant (likely, challenging or worst case) 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 events or planning of emergency response measures. If only one scenario is selected in terms of worst case or worst plausible case, this approach treats uncertainties according to Paté-Cornell's level 1, and level 2 (see section 2.3) respectively. If a relevant set of both likely and worst case scenarios are analysed, this can be a representation at level 3 or close to level 4.

2.4.1.1 Dutch example of a scenario-based approach for road tunnels

The aim of the Dutch scenario analysis is to test the design against established safety objectives and requirements (PIARC, 2008). The focus is on self-rescue and emergency response. The safety objectives and requirements are as follows (PIARC, 2008).

- Traffic handling (prevention).
 - **Objective:** Emergency procedures will need to be in place to direct traffic flows around the tunnel in the event of incidents.
 - **Assessment criteria:** Traffic flow will be sufficiently restricted. Traffic jams in the tunnel will be prevented as much as possible. If traffic jams do occur in the tunnel, they will be cleared as quickly as possible. A diversion route must be set up if the tunnel has to be closed.
- Dealing with incidents (preparation).
 - **Objective:** The combination of measures and provisions by the management organisation and emergency services must be such that the consequences of any relevant types of incidents can be limited as much as reasonably possible.
 - **Assessment criteria:** Injury must be limited. Damage to tunnel must be limited. Duration of tunnel (tube) closure must be limited.
- Self-rescue (correction).
 - **Objective:** The conditions of the building decree must be met.
 - **Assessment criteria:** The capacity must be adequate to allow unobstructed escape to a safe area.
- Emergency assistance (repression).
 - **Objective:** The location of the incident is sufficiently accessible for the emergency services from the tunnel entrances.
 - **Assessment criteria:** The period of time between the moment the emergency service arrive at the tunnel access point and the moment they reach the location of the incident may not exceed 10 minutes.

The method procedure includes the following steps (PIARC, 2008).

- Selection of the analysis team.
- Definition of safety criteria.
- Description of the tunnel system.
- Selection of relevant scenarios.
- Analysis of effects and consequences (qualitatively in time-steps).
- Evaluation of the results.

The selected scenarios should be balanced, realistic and likely (higher event likelihood than $1 \cdot 10^{-6}$ should be managed), and functional, i.e. the safety objectives are challenged or addressed. Each scenario is analysed in time steps i.e.: run-up and disruption, incident, detection/alarm, internal emergency service assistance (tunnel operator), external emergency assistance and lastly reopening of tunnel. Input is, for example, the type of ventilation, emergency lighting, stakeholder involvement, rescue service intervention, drills and exercises. In general soft criteria are used.

The result is identified possible weak spots in the tunnel system as a whole and optimization of the management of the processes before, during and after an incident. Furthermore, the description of scenario developments is an excellent communication tool.

The frequency of a scenario play a role in the decision on additional safety measures: expensive measures only affecting low probability scenarios are not implemented. This could be formulated as a decision principle.

2.4.1.2 French Scenario-based approach for verification of safety

The French safety objective is to ensure safety for road users and to enhance their ability to rescue themselves through proper tunnel equipment and procedures (PIARC, 2008). The following main tools are used to ensure safety.

- Reducing accident likelihood by complying with widely accepted practice.
- If prescriptive standards are not followed a comparative safety assessment is performed to evaluate whether deviations are acceptable or not.
- Measures intended to reduce the risk of accidents are listed.
- System and component failure is assessed, the absence of common failure modes for safety equipment is checked.

The main tools for verifying this are as follows.

- Quantitative assessment of frequencies and trigger events.
- Semi quantitative ranking of trigger events using a risk matrix.
- Quantitative analysis of a set of scenarios to assess smoke movement and the possibility for self-rescue.

2.4.2 System-based approach (QRA)

The second group of risk analysis methods are what PIARC call system based, but are more commonly known as a QRA. Unlike the scenario-based approach where a few scenarios are chosen, all relevant scenarios which can affect the criteria are taken into account. Both causes for incidents and system failures (left side of the bow-tie model) and analysis of the consequences (right side of the bow-tie model) are included in the analysis. Usually this is done through utilizing fault trees and event trees. In this way very many different scenarios can be represented.

The output is the probability of incident occurrences and the resulting consequences (usually in terms of fatalities). This output is often presented in terms of individual risk

(highest likelihood for an individual fatality), and societal risk (displaying the likelihood as a function of the number of fatalities). Note, however, that there is relatively little data on incidents in road tunnels and even less information on tunnel fires. Incident rates vary between tunnels depending on factors such as country, location, geometry, etc. However, in most cases it is unavoidable to use general data which is why corrections, if possible, ought to be performed.

An important category of accidents involving multiple vehicles is particularly bound with uncertainties at the present (PIARC, 2008). Furthermore, in terms of consequences, prediction of fatalities and injuries is difficult, as is modelling of human behaviour, exposure and effect on humans. Many countries use system-based approaches, for example The Netherlands, Austria, Switzerland and Norway. In theory a system-based risk analysis correspond to Paté-Cornell's level 4 (see section 2.3). This means that uncertainties are described with the only limitation of method assumptions. The uncertainty is, however, large as different methods can vary considerably (PIARC, 2008, Ferkl and Dix, 2011).

2.4.3 Evaluation

According to the PIARC report on risk analysis for road tunnels, the following types of strategies can be adopted to evaluate compliance of tunnel safety (PIARC, 2008):

- expert judgement,
- prescriptive standards or guidelines,
- scenario-based criteria, and
- system-based risk measures (Individual or societal risk or cost-effectiveness or a combination).

2.4.4 Recommendations for the practical use of risk analysis

The same report also includes several recommendation concerning the execution of a risk analysis (PIARC, 2008):

- Whatever method used it is a more or less simplification of the real conditions.
- The choice of criteria, risk evaluation and choice of method are not independent.
- Whenever possible use specific data, if not possible, correct for data origin.
- Specific features may be included in a risk analysis model which is not valid for your tunnel.
- Risk analysis should be performed by experts with sufficient experience and understanding of the methods they use.
- The result of a QRA should be interpreted as an order of magnitude and not as a precise number. Risk models invariably deliver fuzzy results, therefore, risk evaluation by comparison is recommended.

2.4.5 Further analysis and recommendations for the use of risk analysis

In a European report concerning the assessment of tunnel safety (Beard and Cope, 2007), the following uncertainties when using models were identified.

- Lack of reality of the theoretical and numerical assumptions in the model.
- Lack of fidelity of the numerical solution techniques.
- Direct mistakes in software.
- Faults in computer software.
- Mistakes in application.
- Inadequate documentation.
- Variability of results may differ by several orders of magnitude.

In the light of the wide variety of possible errors it is thus important that models are.

- Thoroughly tested.
- Conducted by an independent person and examined by a second independent person.
- Verified by a trusted regulatory framework.
- A model used for fire safety design rely on three legs.
 - Fire model (has the potential to be valuable): assumptions must be clearly documented (all models make assumptions), software should be open and transparent or thoroughly tested.
 - Methodology of use which is generally acceptable and encourage a user to be explicit.
 - Knowledgeable user.

2.5 Verification and evaluation of risk and safety

Safety needs to be evaluated in order to reach the best decision. Many factors must be considered when safety is to be verified and evaluated. These include: overall context, the likelihood and magnitude of the risk, the nature of the risk, the underlying activity and possible safety measures. It is inevitably a judgemental call to evaluate on what premises the risk can be said to be low, and what is regarded as important and what is not.

Important points in the risk evaluation process are (Fischhoff et al., 1981, Renn, 2008):

- Stakeholders perception of the risk.
- The benefit of the risky activity (also perceived benefits!).
- The nature of the risk.
- How the benefits and risks are distributed.

In practice this may mean that numerical risk estimates are interpreted as, e.g., “the risk is low”, which is then tested against other interpretation such as “the risk is much feared”.

According to different schools of thought, risk evaluation can be made based on many different assumptions. Hermansson writes about different views of risk evaluation from four different fields: technical, ethical (philosophical), societal (sociology) and economical (Hermansson, 2009). In the technical field a quantitative risk analysis may be performed in which engineering and statistics is used to create a measure of the risk in the shape of a risk curve or a number which may be evaluated against a risk criterion of the same sort.

Within the field of economics, risk evaluation is done through CBA: if the risk activity is beneficial it should be accepted and if risk control options are beneficial they should be installed. The whole world is seen through the lens of insurance and the view is that since society is so large and diversified we all win if the system as a whole wins. Risks may also be evaluated by ethical and social factors, such as fairness of the risk and benefit distribution.

2.5.1 Technical risk evaluation and risk criteria

In many countries different industries technical risk acceptance criteria are used or partly used to evaluate safety. The overall design or decision process is then often called risk informed or risk based, since it is clear that the result of the risk analysis affects the decision or design. Most often a risk criterion is expressed using a risk measure of individual and/or societal risk. Individual risk is often expressed in terms of likelihood of death and the societal risk in terms of a risk profile of expected consequences and likelihood for the affected population, i.e. a cumulative expression of the risk.

However, several studies show big deficits both concerning the quality of the risk analysis, the risk criteria and the verification process. A Norwegian study (Vinnem, 2010)

on the risk evaluation of a Liquefied Natural Gas (LNG) plant showed that the authorities lacked the stamina and expertise to critically review the judgements and data in the risk analysis and that the risk criteria was strangely formulated in favour of the LNG plant. Solutions for improvements include using predefined software, scenarios, and assumptions so that no matter who performs the analysis the results should be the same.

A general principle for risk analysis should be to show how risks best can be reduced rather than to demonstrate that deviations from accepted practice are defensible. The main reason for this, is that risk analysis process might not yet be considered very robust with too many assumptions and simplifications, which easily can be manipulated. For more details regarding the robustness of risk analysis, see (Hall, 1999) or (Ferkl and Dix, 2011).

2.5.2 Economical risk evaluation

A central aspect of economics is that societal resources are scarce and economy is the theory of how to maximise the utility. Thus risks should be accepted as long as the benefits are larger than the costs. Often costs and benefits are expressed in monetary units in order to compare them. One obvious problem is how to put a price on all benefits and costs. Many methods have been developed for this purpose but critics claim that economics have failed on this point.

2.5.3 Societal and ethical risk evaluation

There are many different viewpoints depending on which values are allowed to govern the evaluation criteria, some of these are:

- Choose the imagined future (decision option) which from a moral perspective is most likely to be sound.
- The distribution of risks and benefits arising from the risky activity should be fair.
- No individual should be exposed involuntarily for risks.
- Individuals exposed for a risk must be included in the evaluation process.

These are all valid ethical perspectives which are to be found in most societies. One problem with this approach is that it is quite subjective and it is not clear when a risk should be accepted or rejected. Furthermore, there are many moral perspectives to choose among, however, that is not surprising considering that a society holds many different beliefs. Preferably a set of moral perspectives which reflect the affected community are chosen.

Dien, Renn and others would argue that this subjectivity is necessary, and further propose to include all stakeholders in a constructive risk-benefit debate to negotiate how the risk should be evaluated. Arguments and discourse may often be better than alternative measures since they are flexible and bring forward all values and interests of the stakeholders. A successful stakeholder involvement reduces the risks for future political instability and economical losses (Renn, 2010a, Dien, 2010, Kinsella, 2010).

2.5.4 Risk framing

In societies risk may include a desire to control future events, and to articulate risk is a way to ask for a specific set of events to occur. In this sense someone or a group may use risk in order to exercise power or to try to attain a certain future objective. Therefore, an important part is how a certain risk is being framed. Stakeholders (everyone who is affected or concerned by a certain risk) may associate a variety of issues with a certain risk and existing indicators, routines, and conventions may act as a filter for what is going to be addressed as a risk. A risk articulated as “urgent”, “dangerous”, or “natural” may lead to different outcomes. Through framing the risk problem at hand the context in which the risk is investigated and negotiated will be affected. According to Renn, framing should be done with all stakeholders and include four main points (Renn, 2010b):

- problem Framing (different perspectives of how to conceptualise the issue),
- warning and monitoring (a systematic search for new hazards),
- screening (establishing a procedure for screening hazards and risks and determining assessment and management routes), and
- determination of scientific conventions (determining the assumptions and parameters of scientific modelling and evaluating methods and procedures for assessing risks and concerns).

This is a process which involves questions about power and knowledge: who has the right to claim to have certain knowledge, to claim that some knowledge is better than others? Every risk framing is a choice between many alternative framings. Therefore, each framing can be questioned and done differently. The inclusion of stakeholders is a central part of the process and it is argued that this is the key point in order to ensure trust and legitimize decisions. Often it is said that the risk evaluation should be rational but what is rational is to a large extent decided by how the problem is framed. According to the sociological viewpoint the whole risk process should be democratised starting with the risk framing and ending with the risk evaluation. Ideally, and put i simple terms, the risk framing objective should be to obtain a broad picture of the risk including many different viewpoints.

2.5.5 General (mixed) theory for risk evaluation

In line with Renn, Hermansson suggests that when the uncertainty is large a wider knowledge base should be sought, i.e., the risk process should be democratised through early involvement of stakeholders (Renn, 2008, Hermansson, 2009). Different principles for risk evaluation and their implications should be discussed and analysed in order to motivate what risk evaluating principle is used (rather than referring to tradition and culture). When the ambiguity and uncertainty concerning the risk are small, more straightforward methods can be used such as using best practice or formal analysis.

Renn summarised the following factors which may influence a risks tolerability/ acceptability judgements (Renn, 2008) as follows:

- risk profile:
 - risk estimates,
 - confidence intervals,
 - uncertainty measures,
 - hazard characteristics,
 - range or legitimate interpretations,
 - risk perceptions, and
 - social and economic implications,
- judging the severity of risk:
 - compatibility with legal requirements,
 - risk-risk trade-offs,
 - effect on equity, and
 - public acceptance,
- conclusion and risk reduction options, suggestions for:
 - tolerable risk levels,
 - acceptability risk levels, and
 - options for handling risks,
- risk evaluation:
 - choice of technology,
 - potential for substitution,
 - risk-benefit comparison,
 - political priorities,
 - compensation potential,
 - conflict management, and

- potential for social mobilization.

2.5.6 UK practice of Tolerability and acceptability

Both in literature and real world problems many attempts are being made to define acceptable levels of risk, e.g. the UK Health and Safety Executive (HSE) have developed a tolerability of risk (ToR) framework in order to efficiently tackle decisions in line with policies and the preferences of UK citizens. Tolerability is a better word than acceptability since one does not really accept risks. In the HSE approach risks are characterized as unacceptable, tolerable or acceptable. In order for a risk to be tolerable it should be reduced to a level that is As Low As Reasonably Practicable (ALARP). Individual risks being in the order of 1 in 1000000 per annum are in the acceptable region (Bouder et al., 2007). Individual risks in the order of 1 in 1000 per annum for the occupational sector and 1 in 10000 for the general public defines the limit of what can be tolerable. The HSE toolkit for ToR is built on the following principles (Bandle, 2007).

- The level of risk judged to be tolerable or acceptable depends on the benefits that are generated by undertaking the hazardous activity in the first place.
- Use best practice when available.
- ALARP is the basis of much UK risk legislation which answers the question what is safe enough?
- Formal risk assessment, if the risk is close to being intolerable, the technology is complex or novel if public/political concern is high. It is the highly structured analysis of the safety failures and the measures provided to prevent these failures which are of interest, not the numbers.
- Cost benefit analysis (CBA) is the main tool to prove a risk being ALARP.

The HSE's approach to decision-making is based upon the following principles and stages.

- Ensure that stakeholders will see the whole process as valid and thereby accept the decisions.
- Definition and characterisation of the issue (including framing and risk measure).
- Examination of options available for addressing the issue and their merits.
- precautionary principle applies (related to uncertainty).
- Adoption of a particular course of action for addressing issues efficiently and on time.
- Implementation of decisions.
- Evaluation of the effectiveness of actions taken.

A key point of the framework is to be trust generating, therefore it is important to base the process on openness, transparency and stakeholder involvement (Guen, 2007).

2.5.7 Drawbacks and delimitations of the HSE framework

The HSE framework is serving the UK and HSE well and has been successful so far (Bouder et al., 2007). Fairman points out that one of its drawbacks is that the ALARP principle do not consider how the benefits and risks are distributed (Fairman, 2007), e.g. whether one person is benefitting grossly while many others are taking the risk?

Furthermore, since CBA most often is the basis for judging ALARP, risks and benefits which are difficult or impossible to express in monetary terms are not included in the analysis. In some areas the purpose is not to achieve ALARP but rather As Low As Reasonable Achievable (ALARA), for example in the food industry. Successful adoption of the ToR framework requires stakeholders to: (1) accept risk as a central concept, (2) be willing to balance safety against costs, and (3) be tied into a policy making regime where they are forced to accept compromises. Attractive as the concept is to industrial stakeholders, it is be less acceptable to consumers (Fairman, 2007).

2.5.8 Risk evaluation principles and guidance in Sweden

A schematic picture of the risk analysis process recommended for Swedish governance can be seen in (Davidsson et al., 2003). In this process ALARP, qualitative criteria and a cost benefit discussion/analysis are used to evaluate which decision options are best.

In order to evaluate the risk it is suggested that one should firstly define how to present estimated likelihood and consequence and secondly to evaluate soft aspects of the risk. These soft aspects include different perceptions of the risk, the characteristics of the risk and the benefit from the risk generating activity. The following recommendations are proposed regarding how to evaluate the risk based on consequence and likelihood estimation, see Figure 3.

- High consequence – high probability risks must immediately be reduced.
- Low consequence – low probability risks are likely insignificant and do not need to be reduced.
- The level of risks being accepted must be in line with the organisation's risk appetite.

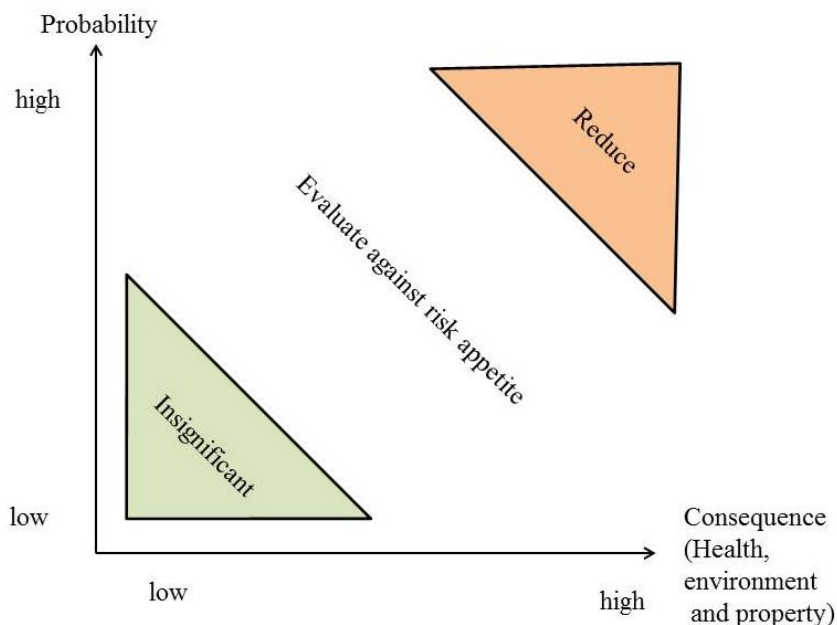


Figure 3 Risk evaluation matrix. Risks in the green are probably insignificant while risks in the red area should be reduced. Risks in between these areas should be evaluated according to the risk appetite of the organisation in question.

For the evaluation of risk, issues apart from the technical aspects of the risk must be included. These include:

- individual and societal perception of the risk,
- the perceived and estimated benefit arising from the activity generating the risk, and
- the characteristics of the risk.

The next step is to summarise all available knowledge and compare the available decision options. Guiding principles for evaluating the various options are as follows.

- Reasonability: No activity should induce risks which with reasonable means (technically and economically) could be reduced or eliminated.

- Proportionality: The total risks arising from some activity or business should be in relation to the benefits (revenue, products, service, etc.).
- Distribution: The risks should be legitimately distributed within the society, and in proportion to the benefits.
- Aversion against catastrophic consequences: Risks should be realised in small accidents which could be managed by societal emergency resources rather than large.

These principles provide guidance and do not have to be fulfilled, often there must be a compromise between them. There are no general accepted levels of risk in Sweden. This may be wise since one should perhaps ask: which decision option is the best, rather than which level of risk is “acceptable” (Davidsson et al., 2003).

We find that, unlike the ALARP principle, the four principles above are more flexible and encompassing. They include the consideration of some fundamental democratic principles and weighing based more on common sense than the solely economic consideration which are covered by the ALARP concept.

Comparison with other types of risks (such as crash risk with fire risk) has the following disadvantages (Davidsson et al., 2003).

- The nature of the risks may be very different.
- Is consideration taken to catastrophic consequences?
- Is consideration taken of the risk distribution?
- Benefits from the different activities are usually not compared, but should be of the same order.

However, there are advantages when using this method for the same type of risks or when for example comparing two alternatives, as many parameters can be excluded from the analysis if they are the same for each case which reduces the uncertainty and scope of the analysis.

Cost and benefit (CBA) evaluation: through weighing costs for risk reducing measures and the benefits arising from them a comparison can be made of how efficient the risk reducing measure may be. Often it is easy to define the cost of the risk reducing measure in monetary units, e.g., the cost of a certain safety system. However, it is harder to evaluate the benefits in monetary units (Davidsson et al., 2003).

In the case of tunnels, for example the benefit of a saved life, environmental values, and societal benefits such as the benefit from less traffic disturbances are not trivial to evaluate in monetary terms. One way to eliminate some of this uncertainty on a case-by-case basis is to pre-specify what assumptions are to be made in regulations or standards, e.g. the American Consumer Product Safety Commission (CPSC) uses \$5 M as the cost of a life.

Risk criterion: A risk criterion may be stated in law or agreed upon before by the authorities in terms of for example societal risk and/or individual risk estimates. These are fixed criteria which, if stated in general terms, do not consider the nature of risk and the underlying activity. This concerns many important factors, such as.

- What are the benefits from the activity?
- What is the public perception of the risk?
- How are the benefits and risks distributed in society or among users?

To conclude, stated methods for risk evaluation: risk comparison, CBA, and risk criterion, have many deficits when strictly used on their own. The knowledge of risk perception, the 4 principles stated above and the context in which each risk exists must be included since these factors contribute significantly.

2.5.9 Choice of risk measure

As Slovic and others have noted, choosing risk measures is very complex and judgmental (Slovic, 2001). The same is valid for the definition of risk, as this significantly affects what questions will be asked and what answers will be considered (Hall, 1999, Slovic, 2001). Risk measure is closely related to the risk criteria. Risk measures have many important parameters, e.g. risk measures such as an F-N diagram or the estimated number of casualties are usually specified per tunnel. This means that if these were fixed criteria and we assume a linear risk per km, a tunnel of 5 km would have about half the risk per km than would a tunnel of 2.5 km indicating that dividing a tunnel of 5 km into two tunnels is favourable.

This is, however, probably not the case since the entrance of a tunnel is where most accidents occur. A way out of this dilemma would be to measure risk per km or vehicle which is commonly done for traffic related risks (Englund et al., 1998). However, it is interesting that this is not always the practice for tunnels, one explanation may be that the tunnel is considered to be a building and that there is a long history of how to specify risk levels for buildings and industrial plants.

Societal (F-N curve) and individual risk is often suggested as a good combination for a risk measure. These are the two most frequent combinations of risk measures used. Individual risk compliments the societal risk through investigating what the highest risk is for any single person. In this sense it takes some consideration of the distribution of the risk (but not in the sense of who benefits and who is exposed). Often in tunnel regulations, F-N lines are defined to represent what is an acceptable level of risk. However, as Kaplan and Garrick point out: "Acceptable" risk implies that risks would be linear, which risk curves are not. They suggests that everyone has a valid perception of risk and that everyone should compare cost and benefits for each design and chose the design with lowest costs, biggest benefits and lowest risk (Kaplan and Garrick, 1981).

To define criteria in the form of societal and individual risk is very technocratic and inflexible. Likely situations would arise in which either risks are accepted even though the public does not want the underlying activity or that risks are not accepted even though a majority may want the cost to be reduced or the benefits from the activity.

2.5.10 The importance of defining the problem and of how it is defined

Before they can be resolved, problems have to be defined. What options and adverse effects will be considered? Once the ground rules of the decision have been set, the decision process may already be determined (Fischhoff, Lichtenstein et al. 1981). Also the very idea and definition of what risk is significantly affects the outcome, or as Slovic put it: "Whoever controls the definition of risk controls the rational solution". In an International Risk Governance Council (IRGC) report on risk governance the phase before the assessment is highlighted and includes the social context, and framing the risk issue at hand (Renn 2010). Kinsella would even take this one step further speaking about the pre-framing, i.e. who is framing and on what knowledge or judgments is the framing based? How are the words being used? Often it is the frame that decide how a risk is treated, not the actual assessment (Kinsella, 2010).

Depending on how a question is asked or what question is asked the answer may vary. In the same way the determining factor in many acceptable-risk problems is the problem definition, issues such as: which options and consequences are considered, what type of uncertainty is acknowledged, also effect the results. The following factors make an acceptable-risk problem difficult and deserve recognition and contemplation (Fischhoff, Lichtenstein et al. 1981).

- Uncertainty regarding how to define the decision problem.
- Difficulties in assessing relevant facts and values.

- Uncertainties regarding the human element.
- Difficulties in assessing the quality in the options that are produced.

According to the IRGC it is important that all stakeholders are framing the issue at hand. Otherwise the results or conclusions may not be accepted since the foundation they are resting upon is not accepted.

In a government report concerning the construction of Swedish tunnels, personal safety was found to be a trade-off between several goals such as safety, costs and political goals (Boverket, 2005a). To identify an acceptable level of safety may not be possible or desirable. Often there is controversy concerning safety issues during tunnel constructions. The problem is not the different points of view but rather that it is not clear what the role is of the various stakeholders and that many different stakeholders are involved. It would thus be beneficial to make the role of different stakeholders clearer even though it not the main objective of this project.

2.6 Acceptable risk

Many argue that the question of acceptable risk is not a scientific question but a political one (Clarke, 1989, Boudier et al., 2007, Beard and Cope, 2007). Others argue that it is an ethical question (Beard and Cope, 2007). Questions such as: "what is the acceptable level of risk?" imply that there would be a universal or partly universal answer to the problem, but as is shown by Fischhoff, Lichtenstein, Slovic and others, this question is misguided and much too simplified.

Through looking at it as a decision problem it is not difficult to find situations when a certain level of risk (higher or lower) is preferred due to certain circumstances being unique to that decision problem (Fischhoff et al., 1981). Each decision problem will be made in a certain context (political, social, amount of resources, values, media interest, etc.) and it will have a unique set of options which are regarded as possible solutions.

The question we should ask is rather: What is the best solution? That is, given the context at that time, what are our options and how do we best evaluate them in order to find the best solution (Fischhoff et al., 1981, Kaplan, 1997, Slovic, 2001)? Fischhoff et al. defined acceptable risk as a decision problem with the following steps (Fischhoff et al., 1981):

1. Specify the objectives by which to measure the desirability of consequences.
2. Define possible decision options including "do nothing".
3. Identify consequences and likelihood of each option.
4. Specify the desirability of the various options.
5. Analyse the options and select the best one.

The act of adopting an option does not mean that the imposed level of risk is accepted in any absolute sense. One does not accept risks, one accepts options that entail some level of risk and benefit in the context of that decision problem. Considering the context of the decision, the option chosen may well not be the least risky option, but hopefully it was the "best" option for all concerned parties (Fischhoff et al., 1981). According to Fischhoff et al., the search for absolute acceptability is misguided and there are no universally acceptable options (or risks).

Regarding the acceptable risk question, it is important to understand the central importance of benefits. Benefits have to be weighed against risks. Why would anyone accept a risk (no matter how small) if there are no benefits (Renn, 2010b)? The objectives of such a risk-benefit communication are:

1. enlightenment,
2. behaviour changes,
3. trust building,
4. conflict resolution, and

5. engagement of stakeholders.

An objective benefit assessment is as important as the risk assessment: which are the benefits? Who benefits and do we want them at all?

The public judges acceptable risk, as well as risk in general, on more than just the level of numerical risk estimates. It is also about who pays, who suffers, and who makes the choice (Hall, 1999). The public perception of risk has been well covered by Slovic and many others. In addition to the expected value, many dimensions are added to the risk concept by the public such as: artificial/natural risk source, catastrophic potential, risk-benefit distribution, belief in personal control, dread, and stigma.

Risk perception is by some called the wisdom of the public. In many ways it is a far more advanced and complex process than formal risk assessment, and it is more real to the lay public. As a result, risk communication and risk management are destined to fail unless they are conducted in a two-way process where the public risk perception is able to bring added value to the overall assessment (Slovic, 1987).

To summarise, acceptable-risk-problems are decision problems: they require a choice between alternatives. This choice is dependent on values, beliefs, costs, and other factors. Therefore, it is questionable whether this complex decision problem could be expressed in terms of a risk number or curve. At best one could hope to find the most acceptable alternative in a specific problem, one which respects the values, perceived risks and benefits at time of the decision.

3 Fire safety regulation

Devastating fires in the 17th, 18th, and 19th century led governments over time to see the need to ensure minimum building requirements (IRCC, 2010).

Some characteristic examples of novel and/or important fire safety regulations are presented to give an idea of the direction in which a future design standard could evolve. In traditional prescriptive regulation, verification of safety is not very complicated and the structure of the regulations may not seem that important. However, as regulation have moved towards becoming more performance-based it has become evident that:

1. verification is not simple, nor straightforward,
2. the structure, goal and purpose of the regulation becomes the focus for verification.

A famous model for a functional, objective-based or performance-based structuring of building regulations is the model of the Nordic Committee on Building Regulation (NKB, 1976). It is based on a hierarchal structure with five levels:

1. societal goals and essential interests of the community at large,
2. functional qualitative requirements,
3. operative quantitative requirements (performance criteria),
4. verification methods (instructions or guidelines for verification of compliance),
and
5. examples of acceptable solutions.

The Inter-Jurisdictional Regulatory Collaboration Committee (IRCC) have developed an eight-tier model for how requirements should be organised and verified as follows (IRCC, 2010).

1. Societal goals and essential interests of the community at large.
2. Functional qualitative requirements.
3. Operative (performance) quantitative requirements.
4. Performance or risk group.
5. Performance or risk level.
6. Performance or risk criteria (measures).
7. Either a, or b:
 - a. deemed to satisfy solutions, or
 - b. performance-based solutions.
8. Verification methods.

To get an impression of practical implementation, some international and national regulations are reviewed in Section 4.1 – 4.4.

3.1 International Maritime Organization (IMO)

IMO (IMO, 2009) have well-structured regulations regarding fire safety. Early fire safety regulations were too vague and disorganised, which became apparent in the early 1990s after the Scandinavian Star accident. The structure in general follows:

- 1) top objective (purpose),
 - a) sub objectives (purpose), and
 - i. functional requirements (what should be done).

Objectives state *why* the regulation has to be complied with, while the functional requirements answer *what* should be accomplished in order to achieve the objectives. After the functional requirements, prescriptive requirements may follow.

Overall fire safety top objectives are in general terms as follows (IMO, 2009).

1. Prevent the occurrence of fire and explosion.
2. Reduce the risk to life caused by fire.
3. Reduce the risk of damage caused by fire to the ship, its cargo and the environment.
4. Contain, control and suppress fire and explosion in the compartment of origin.
5. Provide adequate and readily accessible means of escape for passengers and crew.

The regulations are structured in different groups of requirements, e.g. prevention of fire and explosion, suppression of fire, and escape, which in turn are specified with a clear purpose and functional requirements (IMO, 2009).

- 1) Prevention of fire and explosion.
 - a) Probability of ignition (sub objective). The purpose is to prevent the ignition of combustible materials or flammable liquids) The following functional requirements shall be met.
 - i) Means shall be provided to control leaks of flammable liquids.
 - ii) ...
 - b) Fire growth potential (sub objective). The purpose of this regulation is to limit the fire growth in every space of the ship. The following functional requirements shall be met.
 - i) Means of control for the air supply to the space shall be provided.
 - ii) ...
 - c) Smoke generation potential and toxicity (sub objective). The purpose of this regulation is to detect a fire in the space of origin and to provide for alarm for safe escape and fire-fighting activity. The following functional requirements shall be met.
 - i) Fixed fire detection and fire alarm system installations shall be suitable for the nature of the space, fire growth potential and potential generation of smoke and gases.
 - ii) ...
- 2) Suppression of fire.
 - a) Detection and alarm (sub objective). The purpose is to detect a fire in the space of origin and to provide for alarm for safe escape and fire fighting activity. The following functional requirements shall be met.
 - i) Fixed fire detection and fire alarm system installations shall be suitable for the nature of the space, fire growth potential and potential generation of smoke and gases.
 - ii) ...
 - b) Control of smoke spread (sub objective). The purpose is to control the spread of smoke in order to minimize the hazards from smoke The following functional requirements shall be met:
 - i) Means for controlling smoke in atriums, control stations, machinery spaces and concealed spaces shall be provided
 - ii) ..
 - c) ..
- 3) Escape.
 - a) Notification of crew and passengers (sub objective). The purpose is to notify crew and passengers of a fire for safe evacuation. The following functional requirements shall be met.
 - i) A general emergency alarm system and a public address system shall be provided.
 - b) Means of escape (sub objective). The purpose of this regulation is to provide means of escape so that persons on board can safely and swiftly escape to the

lifeboat and life raft embarkation deck. The following functional requirements shall be met.

- i) ...
- 4) Operational requirement (top objective).
 - a) Operational readiness and maintenance (sub objective). The purpose is to maintain the effectiveness of the fire safety measures the ship is provided with. The following functional requirements shall be met.
 - i) ...

3.2 NFPA 101 Life Safety Code 2009 Edition

NFPA 101 is an American standard for buildings (NFPA, 2008). To a large extent it is very prescriptive describing in detail what fire protection a building should have depending on the type of activity (e.g. hospital, restaurant, etc.). The demands are higher for newer buildings. However, the standard has also opened up for performance-based design through a concept of equivalency and equivalent compliance which means that nothing in the code is intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, etc. Implicitly a scenario based verification method is assumed.

If prescriptive requirements are not fulfilled, a design should comply with the overall objective and the performance criterion:

5.2.2* Performance Criterion. *Any occupant who is not intimate with ignition shall not be exposed to instantaneous or cumulative untenable conditions.* (NFPA, 2008)

The method for showing compliance is by scenario analysis using up to eight design fire scenarios depending on what prescriptive requirements are violated. The design fires are challenging and address various fire safety relevant issues.

The standard has three main goals. The first goal is to:

“provide an environment for the occupants that is reasonably safe from fire by the following means:

(1) Protection of occupants not intimate with the initial fire development

(2) Improvement of the survivability of occupants intimate with the initial fire development” (NFPA, 2008)

The second goal is that life safety should preferably be provided also during other hazards than fires using the same methods as those used in case of fire. The third goal is that reasonably safe crowd movement should be provided. We note that reducing the occurrence of fire is not emphasized.

At the same time the standard is based on three main objectives:

1. occupant protection for those who are not intimate with the initial fire development for the time needed to find a safe place,
2. structural integrity for the time needed to ensure safety of the occupants, and
3. systems should be effective, reliable and maintained.

The standard is further very well structured and the prescriptive requirements for each type of occupancy gives a good idea of what is required in terms of fire safety.

3.3 NFPA 502

NFPA 502, or Standard for Road Tunnels, Bridges, and other Limited Access highways, is an American standard (NFPA, 2011). It contains minimum fire protection and fire life

safety requirements. NFPA 502 does not have the same structure, or the same opening for performance-based solutions as are found in NFPA 101.

Section 4.3.1 of NFPA 502 explains the minimum scope of an engineering analysis of fire protection and life safety requirements. Factors that should be “fully considered” include certain types of scenarios for emergency planning, built-in fire protection features, evacuation, and emergency aspects.

The standard further defines five tunnel categories: X, A, B, C and D, for which minimum fire protection systems are either mandatory, conditionally mandatory or not mandatory.

Concerning structural protection the objectives are: (1) prevent structural collapse, and (2) minimize economic impact due to tunnel closure. The verification process is based on a design fire and a criterion for the performance of the structure.

There is no clear overall objective or performance criteria; instead there are specific criteria for several factors. For example, concerning egress, the objective is to ensure that the Available Safe Egress Time (ASET) is sufficient. Calculation procedures and tenability criteria are presented in Annex B as an informative text. The analysis will show, depending on tunnel class whether, for example, the minimum requirement of spacing between exits of 300 m is sufficient or not.

To summarize, the standard presents prescriptive minimum requirements depending on tunnel class. Next it asks for a fire protection engineering analysis to be carried out which at the minimum considers several pre-defined factors. If this analysis shows that some factors using the minimum requirements are critical, harder requirements are used for the particular factors. It thus has an opening for performance-based solutions within certain minimum limits. However, each factor seems to be evaluated by itself. For example, there is no possibility of changing from high to low class fire structural protection when installing a fixed fire fighting system (NFPA, 2011).

3.4 Verifying building works fire safety in Sweden

When designing for fire safety in buildings, the overarching legal requirements are provided in the same documents as for tunnels, i.e. the Planning and Building Act (2010:900) and Planning and Building Ordinance (2011:338). But, contrary to the tunnel situation, the Swedish National Board of Housing, Building and Planning has issued rather specific mandatory requirements for buildings, the Building Code. This Building Code BBR19 (Boverket, 2011a) 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 overall objectives for fire safety of the code correspond to the five basic requirements described in section 1.1. For example occupant safety should in principle always be fully provided while the spread of fire should be restricted. However, these requirements assume a fire, which is why they do not touch issues concerning reducing the likelihood of occurrence, although naturally this is also a requirement. The frequency of fire is considered in the second of the five general requirement for building works, see section 1.1.

The code separates the requirements from the recommendations which in turn provides 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. The designer can either choose to follow the prescriptive requirements and the general recommendations which is known as the simplified design option, or he can use an alternative approach (performance based) in which he follows the requirements, but not the general recommendations.

The Swedish National Board of Housing, Building and Planning also issued guidelines for the verification method for performance-based solutions (known as the analytical design option), Boverket (2011b). 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 formal base for the verification is mainly the scenario analysis. The designer can apply other higher order methods like a quantitative risk analysis or qualitative methods but then there are no further recommendations presented apart from the general procedures on analytical design.

As the scenario analysis is an implicit method, no formal considerations have to be taken with respect to scenario frequency. Instead the method focuses on the consequences of the scenarios and the guideline for analytical design presents information on design scenarios and other relevant data for the analysis. The choice of design values are supposed to cover most of the possible scenario outcomes.

The 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.

Still, it is assumed that most design will follow the simplified approach and the analytical design option will be used only occasionally for more unusual constructions and for buildings where this option is required, e.g. for high rise buildings, larger assembly buildings and larger hospitals.

4 Evaluation and exploration of tunnel safety systems

In order to verify safety it is useful to know in which ways this is possible and which evaluation methods cover or evaluate which systems. In this chapter, as a reference, we will consider a tunnel longer than 500 meters for which the EC directive applies. This chapter will assist in understanding what verification tools actually verify. Therefore each safety system is explained quickly and then categorized according to how its benefit to safety can be estimated.

4.1 How can a tunnel safety system be evaluated?

No method fit all purposes, this section aims to highlight which methods that are available for evaluating a tunnel fire safety system. For example, a QRA only evaluates systems for which there is statistical or expert knowledge concerning quantitative data.

Requirements in regulations are closely connected to the method used for evaluation, . For example, a prescriptive requirement is simply verified by showing compliance. If the regulation opens up for a fire safety engineering approach, verification may not be straight forward. Many factors may need to be verified such as the models used, assumptions being made, and data used.

Furthermore there is also the aspect of the whole design process, did we build the right thing, did we build it right, and is it working? Thus there are three aspects of verification; prescriptive, fire safety engineering, and verification and validation of the design process. Prescriptive and fire safety engineering methods available for evaluation in this report are presented in the following sections.

4.1.1 Prescriptive verification

Prescriptive requirements can preferably be used for functions which are required by any legal document and for systems which are standardised. There is much to gain in standardising the interface towards the road user, for example through standardising the appearance of all safety equipment, signs and signals. Experience also shows that prescriptive requirements are good as a basis for the design. They also offer an implicit level of acceptable safety. Verification is straightforward and simple, either you comply with the requirement or you do not. Uncertainty is implicitly handled through the specification of requirements which have evolved over time, often as a response (reactive) to accidents, at least regarding safety issues.

4.1.2 Fire safety engineering

Fire safety engineering is divided in the following types of methods commonly used for verification purposes: QRA, scenario analysis, egress analysis, design fire, failure analysis and CBA. Methods used in fire safety engineering will can also be classified according to how they treat uncertainties, see section 2.3. These methods are only applicable if the requirements are expressed in terms of performance. Each method is dealt with separately below.

4.1.2.1 Systemic, quantitative risk analysis (QRA)

Systemic risk analysis, also called QRA, see section 2.4.2., includes both aspects of the bow tie model presented in section 2.2. That is both estimation of accident likelihood and consequences. A QRA requires in general both skilled resources and relevant statistics to be useful. The treatment of uncertainties is in Paté-Cornell's classification level four, see section 2.3.

4.1.2.2 Scenario analysis

This is a qualitative and/or quantitative analysis in which different scenarios are tested against the tunnel system and the action of the police, operator, etc. The method implies that scenarios are only described in terms of their consequences and the frequency for

each scenario is implicitly included in the choice of scenario and the derivation of the consequences, i.e. a conservative approach is taken.

The scenarios included in the analysis specify what the tunnel should handle, i.e. a functional requirement. Scenario analysis can be performed on level zero, one or two according to Paté-Cornell (see section 2.3.2). If only one scenario is included it is theoretically either level one (worst case) or level two (plausible worst case). In practice, more than one scenario is usually included in the analysis in order to include different outcomes and increase the certainty in the decisions based on the scenario analysis.

How the scenarios are created and selected is treated in ISO 16733. As is stated there, the selection of scenarios is a critical step in fire safety engineering. The potential number of scenarios is infinite and a manageable set has to be identified. Each fire safety design objective has its own set of scenarios being relevant for challenging the objective. The resulting design solution should be conservative (ISO, 2006).

A scenario is characterized by specifying: fire initiation, growth phase, fully developed phase, extinction, fire and smoke spread routes, and interaction with fire protection features (ISO, 2006).

4.1.2.2.1 Design fire

A design fire scenario is defined as “a specific fire scenario on which deterministic fire safety engineering analysis is conducted”, and a design fire is defined as “a quantitative description of assumed fire characteristics within a design fire scenario” (ISO, 2006, p. 1,2). Each design fire scenario is selected to represent high-risk clusters of fire scenarios.

4.1.2.2.2 Egress analysis

An egress analysis may be included in a safety analysis using a scenario based approach. The egress analysis compares evacuation time with time available before untenable conditions occur. Unlike for a QRA, an egress analysis is mainly focused on the possibility for a safe evacuation rather than the calculation of the number of persons not able to evacuate before untenable conditions occur. The design conditions, using the scenario based approach, is that all persons must be able to escape safely in all scenarios investigated. In that sense criteria for a safe evacuation can be defined; see for example section 2.4.5 in which criteria for human safety are presented. Often only a few representative scenarios are evaluated.

4.1.2.3 Failure analysis

This group of methods focuses on the left hand side of the bow tie model, i.e. the failures that lead to an accident. Methods for analysing these types of failure are for example Failure Mode and Effect Analysis (FMEA). Reliability engineering is an engineering field which deals with the study, evaluation, and life-cycle management of reliability. The ability of a system or component to perform its required functions under stated conditions for a specified period of time. Methods to minimize failure are usefully combined with a scenario analysis as a scenario analysis focus on the right hand side of the bow-tie model. Obviously these methods reduce the risk and uncertainty but they are not easily classified according to the scheme of Paté-Cornell.

4.1.2.4 Cost Benefit analysis (CBA)

In a CBA costs and benefits are weighed in a utilitarian manner. A CBA is often performed on level 3, i.e., expected values are used. According to Ferkl and Dix there is a danger in using these methods when the probabilities are small and the uncertainties are large (Ferkl and Dix, 2011), which is the case for road tunnels. However from an economic perspective the theory works as long as the added probabilities are relatively large considering all tunnels in a nation or region in the decision. A CBA is in principle based on data from a QRA.

4.1.3 According to the safety circle

Taking advantage of the safety circle defined by PIARC, see section 2.2, safety is sequentially divided into the following type of measures.

- **Pro-action:** eliminating the root causes, for example through training or design.
- **Prevention:** reducing tunnel accident probabilities, for example through reduced speed.
- **Preparation:** treatment of emergencies.
- **Mitigation:** mitigating consequences of tunnel accidents.
- **Intervention:** rescue teams.
- **After-care:** taking actions to return to normal operation.
- **Evaluation:** learning from exercises and operation.

Each tunnel safety system will be categorized according to the safety circle. The reason for doing so is to achieve a good priority and balance since it in general holds true that (PIARC, 2007):

1. safety measures that function early in the circle are most cost-effective, and
2. all areas should, however, be addressed. Each area is vital for ensuring high functionality and availability.

4.1.4 Context, costs and benefits

Safety systems which are mandatory or prescribed by law do not need to be evaluated through an advanced analysis; they have to be installed anyway. For this either prescriptive or functional requirements are sufficient. The aim is to be able to prioritize which parameters should be analysed more in detail. The following rules will be applied for this purpose.

- Very cheap systems in relation to perceived benefit do not need a detailed evaluation, but can be prescribed by either prescriptive or functional requirements.
- Obligatory requirements from law will not be analysed.
- Systems which would gain in becoming standardised from a safety perspective will be indicated.
- Systems which are specific to each tunnel will be indicated.

4.2 Tunnel safety functions or systems

In this section all systems, measures and parameters which either highly affect the fire safety or controls it are presented. The list covers all systems known to the authors to affect tunnel fire safety (Kim et al., 2007, DARTS, 2004, PIARC, 2007):

4.2.1 Organisation

These are very important aspects of safety (often it is due to deficits in the organisation or management that large accidents happen or escalate). The organisation part includes:

- a) safety documentation,
- b) correct maintenance,
- c) emergency plan, and
- d) instruction and training of personnel.

4.2.2 Reliability and redundancy

For all systems the failure rate should be specified and verified. Some systems may be very important, either by themselves, or since many other systems depend upon them. Therefore, some systems need to be made more reliable or redundant. Minimum

requirements for tunnels regulated by law in terms of redundancy include the following aspects.

- a) Emergency power supply. This is often regulated in law. Rather than having a separate emergency generator one could also connect to another independent power supply.
- b) Proper and redundant lighting.
- c) Redundancy in general.

4.2.3 Traffic and incident management

The safety provisions are aimed at a safe and steady flow of traffic and an 'as well as reasonably possible' prevention of incidents and response to disruptions in traffic. Many aspects of the safety circle are addressed by this category of measures. This deserves an organisation in the sense of perhaps an operation centre, as well as an incident team.

Traffic and incident management requirements include the following.

- a) Speed control.
- b) Separate lanes for trucks: (slower brakes and acceleration and more awareness). Will reduce congestion when there is a heavy inclination in or near the tunnel.
- c) Interdiction to overtake.
- d) Lay by: The benefit arising from turning bays is almost impossible to estimate quantitatively. Therefore, it is most likely evaluated qualitatively. It is, however, mandatory for long (1500 m) bi-directional tunnels with traffic higher than 2000 vehicles per lane and day.
- e) Traffic control system.
- f) Accident warning system: In case of an accident, suitable information and actions are distributed on display boards and traffic signals.
- g) No entrance when queues: To reduce the likelihood of having queues inside the tunnel.
- h) Middle barrier: A middle barrier reduces the risk of head-on collisions.
- i) Height detection at tunnel entrance: At a suitable distance before the tunnel the height of the vehicles can be checked in so that vehicles that are too high can be stopped in time.
- j) Traffic barrier and traffic signals: These comprise traffic light and mechanical barriers and are in general very cheap and basic requirements why prescriptive or functional requirements may be used.
- k) Entrance control: The purpose of this measure is to reduce the consequences of accident in order to force Heavy Goods Vehicles (HGV) to stop and cool down before entering the tunnel
- l) Escorting Dangerous Goods Vehicles (DGV).
- m) Obligatory distance to other vehicles.
- n) Lateral clearance: A wide right lane for trucks reduces the likelihood for collisions and a wide side lane for rescue vehicles facilitates the access for emergency vehicles.
- o) Traffic signals inside the tunnel: This includes lane use control and other means to control the traffic by signage. The benefit is very difficult to estimate why evaluation through a safety concept is recommended.
- p) Incident management system: tools and procedures to quickly deal with road incidents.
- q) Road surface (friction): This is a preventive measure to limit the amount of accidents.
- r) Limitation of DGVs: In EU this is usually evaluated through using the Dangerous Goods Quantitative Risk Analysis Model (DGQRAM) method (PIARC, 2008). It is a trade-off between the risk of driving through the tunnel and the risk of taking alternative routes.

- s) Limitation of HGVs: This is in use in for example Switzerland. According to French statistics 60-70 % of all fires involving HGVs are caused by overheated breaks.
- t) Bi/uni-directional tunnel tube: Affects the emergency and ventilation strategy. If traffic is to exceed 10000 vehicles per year and lane in 15 years bi-directional tunnels are mandatory for new tunnels.
- u) Information at entrance.

4.2.4 Fire prevention

In the case of a fire the hazard may rely on mitigation efforts. Typical fire preventions requirements include the following aspects.

- a) Road surface adaption: The road surface should reduce the evaporation of toxic liquids and allow for fast draining.
- b) Liquid sump and drainage: Within the EU it is mandatory to have drainage for flammable and toxic liquids where transport of dangerous goods is allowed. The benefit is difficult to evaluate. However, it helps in case of flooding, fire extinguishing and toxic liquid. This may best be specified through a functional requirement.
- c) Cables under the road: This allows for maintenance and service work without disturbing the traffic. Furthermore, the cables are to a large extent protected from events occurring in the tunnel tube. This also increases the availability.
- d) Tunnel alignment: HGV fires are often caused by overheated breaks.
- e) Hand held extinguishers: These are necessary to facilitate first response by road users. The benefit is perceived to be big and the cost minor. The spacing varies between 50 m and 250 m for various national guidelines. The need and spacing of hand held extinguishers may be prescribed with a given capacity. Furthermore, an extinguisher removal alarm is recommended.
- f) Fixed fire suppression systems: Fire suppression systems are quite expensive, but they also have a big benefit and high efficiency at reducing potential catastrophic fires to minor fires. Risk and cost-benefit assessments considering large catastrophes with consequences in terms of economic and infrastructure impact, reparation and closure time may be suitable methods for evaluating the need. CBA are used today in many countries for this purpose. For large and important tunnels the benefits will likely outweigh the costs.
- g) Inflammable lining.

4.2.5 Fire detection and monitoring equipment

Analysing the benefit from detection and communication systems is rather difficult and is in general not included in QRA or CBA. Scenario analysis may be a useful approach together with functional requirements. Prescriptive requirements could also be useful and are presently already in law. Note that the benefit from each detection system depends on the other detection systems installed. A more detailed level than detection in general would thus not be very functional. Typical requirements for fire detection and monitoring equipment are as follows.

- a) Automatic fire detection systems: Smoke detection in tunnels is difficult due to the exhaust from vehicles and the ventilation. Heat detection should have fewer false alarms.
- b) Manual fire detection system (alarm buttons): This is very cheap and broadly accepted safety equipment. Prescriptive requirements with spacing of 50 meters may be used for all tunnels.

- c) Emergency telephones: As with alarm buttons this is considered a basic and cheap installation. Prescriptive requirements may be used since it is a basic installation. Method for evaluating its benefit is through safety concept.
- d) CCTV: Closed-Circuit Television (CCTV) might be needed also for the traffic management and incident management. Thus it may be a cheap system offering several improvements.
- e) Automatic incident detection: By analysing the surveillance data stopped vehicles or slow traffic can be identified in order to get the attention of the operator.

4.2.6 Fire fighting

All fire fighting tools affect their utility internally, e.g. if a sprinkler system is installed the benefit from hand held extinguishers will be reduced. Therefore, a general concept for all extinguishing systems can be regarded as positive added value for the fire safety, e.g. the benefit from fixed water and hand held extinguishers depend on each other. Typical requirements related to fire fighting include the following aspects.

- a) Emergency access for fire fighters: This is about providing access to the tunnel for the fire brigade. In general it can be expected to be very costly and the benefits are difficult to estimate.
- b) Water supply and hydrants: Pressurised fire hydrants have a higher capacity than hand held extinguishers. However, the cost is also higher. According to the EU directive there should be hydrants at least every 250 meters for tunnels longer than 500 meters. In Sweden, however, the requirements are at least every 150 m for new tunnel and 250 m for existing tunnels.
- c) Fire department location: Often the fire brigade start the operation at a relatively late stage due to that the same smoke apparatuses and strategy are used as for extinguishing house fires and that it may take time to arrive and prepare the operation. The benefit is difficult to estimate as their chances of extinguishing the fire early are relatively small. Cross-passage for rescue vehicles: For twin-tube tunnels longer than 1500 meters, a cross passage for rescue vehicles is mandatory within EU and the TEN network.
- d) Separate gallery for emergency vehicles access: This is not used in general. Optional.
- e) Fire brigade power tool sockets: This is seldom legislated, the benefit from such a system is difficult to evaluate but can be expected to be minor. The cost, however, would also be minor, maybe this could be up to the fire brigade.

4.2.7 Evacuation and risk to life

This section concerns human safety in case of accident. Typical systems which have an impact on evacuation are as follows.

- a) Automatic alarm system: As soon as a fire is detected lights, and emergency sound gives attention to the road users.
- b) Ventilation system: A ventilation system is a necessity in longer tunnels and short tunnels with dense traffic. It improves the conditions upstream and/or downstream of the fire depending on how it is used and what the need is in the tunnel. Either the smoke can be extracted through a transversal ventilation system, or the smoke is transported along the tunnel in a longitudinal ventilation system.
- c) Ventilated escape routes.
- d) Emergency lights: The benefit or impact from emergency lighting is very difficult to evaluate why it is most often prescribed in terms of a prescriptive requirement. This also includes emergency exit signage and/or light.
- e) Loudspeakers: If there is a 24 h traffic management team this would not add any extra cost. However according to PIARC, communication in the tunnel through

loudspeakers is very difficult due to high background noise and bad acoustic. Radio communication systems: Radio communication through the radio in each vehicle is a way to speak to all road users. This may be quite cheap if there is a 24 h traffic management central who could then instruct the road users what to do for each specific emergency.

- f) Parallel escape tube: Benefits are less risk to life. Depending on tunnel structural design it may be either very cheap or expensive to make use of a parallel escape tube. A QRA or a scenario analysis could be suitable methods to evaluate the need.
- g) Emergency cross-passage: Depending on the tunnel construction type, for uni-directional tunnels it may be cheap to install many emergency doors. The spacing of emergency cross-passage to evacuation path or safe haven is often prescribed and varies between 100 m and 500 m. The cost varies much depending on how the tunnel is designed. Therefore, CBA could be used to optimise this matter or to arrive at an efficient overall design taking into consideration also other safety systems. This is, therefore, not recommended to be prescribed for all tunnel designs. Risk analysis may also capture this issue but uncertainties are quite large when it comes to human behaviour when evacuating a tunnel. Emergency doors leading either to a safe chamber or a safe escape route.
- h) Asymmetric openings: The objective of this safety measure is to avoid smoke to go out from one tunnel opening and into the next.
- i) Lay-by with emergency station before tunnel portal: This is used for the emergency service and is mandatory for long tunnels.
- j) Emergency walkways: Mandatory for new tunnels.
- k) Wall appearance: Human behaviour and perceived traffic safety are important aspects, but the benefit is difficult to evaluate quantitatively.

4.2.8 Structural safety

The purpose of the following measures is to protect the structure from collapsing and long reparation work.

- a) Structural fire resistance: This is often specified through a functional requirement specifying a design fire which the lining and structure should withstand. Within EU the main structure shall ensure sufficient level of fire resistance to avoid a collapse which can have catastrophic consequences. However, the benefit from fire resistance highly depends on other installed systems such as fixed fire suppression. This includes insulation to protect bearing structure from heat and the use of suitable concrete which resist fire well.
- b) Equipment resistance to fire: This is often specified through simple functional requirements. The end benefit could be difficult to evaluate.

4.3 Summary of safety systems, their importance and the possibility of evaluation

In Table 1, the safety measures described above (section 4.2) are evaluated against the effect in the safety circle (section 4.1.3), the context and perceived benefit in relation to the cost (section 4.1.4), and the means for verification (section 4.1). The purpose of this evaluation is not be precise, rather it is used as a tool to indicate which safety systems are evaluated by which method, and when prescriptive and/or functional requirements should be formulated.

Table 1 Evaluation of means to verify and evaluate tunnel safety systems and functions

Safety system	Safety circle phase	Cost efficiency ²	Context			Verification				
			Obligatory	Standardised	Tunnel specific	Prescriptive	QRA	Scen. analysis	Failure analysis	CBA
<i>1 Operation and Organisation</i>										
a Safety documentation	All	High	X		X	X				
b Correct maintenance		High	X		X	X			X	
c Emergency plan		High	X		X	X		X		
d Instruction and training		High	X		X	X				
<i>2 Reliability/Redundancy</i>										
a Emergency power supply	pro-active and prevention	High	X	X		X		X	X	
b Proper and redundant lighting		High	X	X		X		X	X	
c Redundancy in general					X		X	X	X	X
<i>3 Traffic and incident management</i>										
a Speed control					X	X	X			
b Truck lanes					X	X	X	X		
c Interdiction to overtake		High	X			X				
d Lay by					X	X				
e Traffic control system		High		X	X	X		X		
f Accident warning system	Also mitigation			X		X		X		
g Avoid queue inside tunnel		High			X	X		X		
h Middle barrier										
i Height detection					X	X				
j Accident beam and signals	Also mitigation	High		X		X				
k Entrance control					X					
l Escorting DGV					X					
m Obligatory distance between vehicles		High		X	X	X				
n Lateral clearance					X	X				
o Traffic signals inside	Also mitigation	High		X		X				
p Incident management	Mainly preparation				X			X		
q Limit DGVs					X		X			X
r Limit HGVs					X		X			X
s Road surface (friction)		High	X	X		X				
t Bi/Uni directional tunnel tube			X		X	X	X	X		X
u Information at entrance			X	X		X				
<i>4 Fire prevention</i>										
<i>Mitigation</i>										
a Road surface adaption					X	X				
b Efficient drainage		High	X		X	X				
c Cables under the road					X	X			X	

² This is an estimated value based on the perceived benefit in terms of safety in relation to the cost

d Tunnel alignment			X		X	X				
e Hand held extinguisher	Also preparation and intervention	High	X	X		X				
f Fixed suppression system	Also preparation and intervention	High			X		X	X	X	X
j Inflammable lining			X	X		X				
<i>5 Accident detection</i>										
a Automatic fire detection	Preparation and mitigation	High			X	X			X	
b Manual fire detection (alarm button)		High		X	X	X				
c Emergency stations at least every 250 m		High		X	X	X				
d CCTV		High			X	X		X		
e Automatic incident detection		High			X	X				
<i>6 Fire fighting</i>										
a Emergency access for fire fighters	Mitigation and intervention				X	X		X		
b Water supply and hydrants			X		X	X		X	X	
c Fire department and connections			X		X	X		X		X
d Cross-passage for emergency vehicles					X	X		X		X
e Separate gallery for emergency access					X			X		X
f Fire brigade power sockets					X			X		
<i>7 Evacuation / Risk to life</i>										
a Automatic alarm system (visual + audio)	Mitigation	High		X		X		X	X	
b Ventilation system			X		X	X	X	X	X	X
c Ventilated escape routes					X	X		X		
d Emergency and evacuation lights and signage		High	X	X		X		X		
e Loudspeakers (voice)		High		X		X		X		
f Radio communication				X		X		X		
g Parallel escape tube					X		X	X		X
h Emergency cross passage					X		X	X		X
i Asymmetric opening		High	X		X	X				
j Lay-by with emergency station before tunnel portal								X		X
k Emergency walkways								X		
l Wall appearance		High	X	X		X		X		
<i>8 Structural safety</i>										
a Structural fire resistance	Mitigation		X		X	X		X		X
b Equipment resistant to fire						X		X	X	X

It is evident that evaluation of safety using only one single method is not possible. In order to evaluate all systems, many different methods have to be used, e.g. a QRA only covers a limited set of the evaluated parameters. It is thus a poor “proof” of overall safety. One reason for this is lack of data and another is that some parameters are not possible to be represented numerically. The scenario analysis covers more parameters. However, in many cases a “magic number” (Ingason, 2008) seems to be the best solution since it allows a system to be evaluated once and for all so it is not repeated in every tunnel project. The question is though how to find the magic number and who should take responsibility for finding it. Prescriptive requirements are sometimes the easiest option when a certain system or function for obvious reasons has to be installed (regulation or common sense).

A qualitative scenario analysis together with a failure mode analysis would capture both sides of the bow tie model (reducing likelihood of failure and accidents and limit the consequences). Furthermore, it is an efficient communication and training tool for the rescue service organisation and procedures.

Another important point is to distinguish between parameters being able to be changed and parameters not being so, e.g. the tunnel cross section highly affects the fire behaviour but is decided by other parameters than fire safety related ones. All the parameters being specific for each tunnel should probably not be verified with a prescriptive requirement. All the parameters which are an interface to the road user should, on the other hand, benefit from being standardised both in function and visual design.

From Table 1 and in particular column three, which specifies where in the safety circle (see section 2.2) the measure belongs, we see that few measures focus on after-care and evaluation. Many measures focus on mitigation. As measures early in the safety circle are more efficient than those later in the safety circle, more measures should focus on pro-action and prevention.

5 Experience from other countries

According to a recent comparison and review of safety design guidelines for road tunnels, even though many road tunnels are built worldwide each year, satisfactory safety measures against fires have not yet been established, or are in the process of development (Kim et al., 2007). In the comparison, which included guidelines from 13 countries and organisations, it was found that most requirements are a function of tunnel length. Another key parameter beside the tunnel length is the traffic volume. The minimum tunnel length for guideline application varies between no value specified to 90 m or 500 m length. In general certain fire safety equipment was included in most guidelines while some equipment was mentioned rarely. It was concluded the lack of knowledge concerning tunnel fire safety is the largest limitation for improving the guidelines (Kim et al., 2007).

During 2010 and 2011 meetings took place between the authors and selected key persons to include practical experience from Australia, The Netherlands, and Germany. Australia was identified in the pre-study as an interesting case study for performance-based tunnel safety. The Netherlands was included since they have demonstrated the use of novel and interesting techniques for tunnel safety validation and verification. Germany was included in the study since their context and way of working was believed to be similar to Swedish practices. In order to obtain new or unknown information semi-structured interviews were conducted. The edited manuscript was reviewed by the interviewee before publication. Note that these interview notes represent the understanding of individual experts.

5.1 Australia

In Australia, tunnel safety has a high priority. Accordingly their tunnel safety is of interest. The authors have met with ARUP which is a world leading tunnel design and consultancy firm, with Shan Raffel who is station officer at Queensland Fire and Rescue Service and with Nick Agnew from the engineering firm Stacey Agnew Pty Ltd.

5.1.1 Peter Johnson and Paul Williams, ARUP

In August 2010 the authors met Peter Johnson and Paul Williams from ARUP at Lund University. Johnson and Williams work with the tunnel design as practicing engineers. Based on their practical experience from the field, in general, “if you have accident detection, simple ventilation system, deluge type (sprinkler) suppression system and some 100 meters between emergency exits you may have a reliable and relatively safe tunnel”. Such a tunnel does not need to always be very expensive, in their mind. A deluge sprinkler system for the proposed Denmark-Germany rail tunnel with a length of 18 km would only cost around in the 10s of millions €. This is a relatively low cost in relation to the overall construction cost of the tunnel. For comparison, a semi-transverse ventilation system would cost some hundreds of M€, and significantly more than longitudinal ventilation. Since tunnels in Australia have toll systems it is relatively easy to perform a Cost-Benefit Analysis since the cost of the downtime and loss of toll revenue can be determined relatively easily, and added to the asset damage and other costs in the event of a fire. Such analysis has shown a fast payback time on sprinklers due to high cost in case of a major fire and a long tunnel closure. Escape doors are relatively cheap in immersed tube tunnels and at the same time extremely critical for rescue. However, if other tunnels they require the use of parallel tunnels and depending upon the spacing and other factors can be costly and a construction risk. In Tokyo 12 fires have been suppressed by deluge type sprinkler systems (6 mm/min) (although no HGV fire), and were also successful in the potentially large Burnley tunnel fire in Melbourne. The view of ARUP is that sprinklers in tunnels is a very cost efficient safety measure.

One practical experience from designing tunnels is that for the fire safety engineers “projects never start from scratch, that would be too expensive, you always start with something in terms of a concept design and some basic idea of fire safety measures”. Furthermore, substantiation of designs through “risk analysis takes time and needs

appropriate inputs; so, even risk-informed design cannot start from a blank sheet. Therefore, prescriptive requirements often form the initial basis of a tunnel project design. However, a performance based approach provides the flexibility to allow for other solutions”. The recent experience is that “Australian fire authorities have tended to add more and more fire safety features to tunnel project requirements and have asked for consideration of increasingly lower probability scenarios”.

A scenario development framework copied from the industrial fire protection field has proven a favourable way to involve stakeholders. The experience is that you come very far with talking through scenarios with stakeholders. “Describe them in words, apply common sense and engineering reasoning. Risk analysis can be used to show that a tunnel project will achieve a reasonable level of safety.”. Each tunnel is unique and needs different solutions. For example, Norway has the world’s longest tunnel with no sprinklers and few emergency exits but instead turnaround points since it only has around 1000 vehicles per day.

In a project you have contractors with the objective of low cost and on-time project completion. And on the other hand, consultants have the objective to achieve safety and approval from authorities. These two can be constantly working against each other. Some advice and general function of the tunnel design process are (Johnson and Williams, 2010):

- fire scenarios and design fires should drive the design and analysis,
- risk analysis follows the design, it does not lead, and
- the process is as important as technical design, involving:
 - early stakeholder involvement,
 - understanding of local cultures,
 - development of good relationships with approval authorities,
 - local legal situation and lawsuits,
 - managing your own risks, and
 - debate, give and take.

5.1.1.1 Burnley tunnel fire

The ARUP representatives also provided a review of the Burnley tunnel fire in 2007. The Burnley tunnel had a wide range of fire safety measures installed including a suppression system with deluge sprinklers (10 mm/min). Often crashes seem to happen at the bottom of a downhill as in this case since it is difficult to brake for a HGV, which was the case in the Burnley Tunnel fire. Potentially this could have been a very large fire involving at least 2 trucks and 3 cars initially and potentially many other vehicles. The suppression system, however, controlled the fire well and the tunnel could re-open after only 4 days. This revealed the message of efficient emergency organisation and clean-up, which is very positive publicity for all involved parties. Furthermore, it allows a faster opening since there is no political process slowing things down (Johnson and Williams, 2010).

5.1.2 Shan Raffel, Queensland Fire and Rescue Service

The authors met with Mr Shan Raffel at SP, 28th of June 2010. Raffel works as station officer at Queensland Fire and Rescue Service. He says that the public demands high safety and “zero harm”. Therefore, safety is as high as technically achievable. In practice this has led to that many systems are duplicated to reduce failure frequencies. In Australia stakeholders are integrated in the pre-design phase. However, for the fire brigade it is a bureaucratic pain due to the amount of documents that are passed around. It is a way, however, to provide the government with evidence that it is doing the best to meet the public expectation for a high level of safety (Raffel, 2010).

5.1.3 Nick Agnew, Stacey Agnew Pty Ltd

Dr Nick Agnew who is an expert in tunnel fire life safety for Stacey Agnew visited SP on the 15th September 2011. Stacey Agnew Pty Ltd is an independent consultancy offering clear thinking, analysis and design in tunnel ventilation, underground fire safety, and associated electrical and mechanical disciplines. Agnew explained the typical tunnel fire safety design process in Australia from a practical viewpoint.

There are three major considerations when determining the appropriate level of safety to be achieved: 1) the community and its expectations, 2) expert opinion and industry practice, and, 3) risk. The contractual framework around individual projects often leads to deterministic approaches which may not relate to those three considerations. Road tunnel fire incidents are very rare and so often the real risks associated with tunnel incidents are not well understood or appreciated by fire brigade or community. Often the designer cannot rely on quantified risk assessment alone and must consider other non-scientific facts and requirements. It is also recognised that the community in general has a heightened sensitivity to any tunnel incident.

As a designer you always start with some basic requirements in terms of: 1) provisions for evacuation and self-rescue which includes smoke control, 2) systems to allow the fire brigade to do their job safely, and 3) asset protection to ensure business continuity. When treated deterministically, this in turn could for example lead to tenability criteria for evacuation: firstly visibility (5-10 m) since it becomes critical first, followed by radiation, temperature and toxicity.

Australia has a new standard for Tunnel Fire Safety, AS4825 that was published in February 2011. The standard covers rail, road, and bus tunnels. The standard has few prescriptive requirements but offers guidance on general fire life safety systems to be included and on the fire engineering process. Overseas standards and guidelines are also considered such as PIARC and NFPA 502.

Designers recognise the importance of fire brigade intervention, especially for asset protection. In Australia tunnel designers, the tunnel owner, and the fire brigades work in a collaborative way. The fire brigade is consulted very early in tunnel projects. The fire brigades typically approve systems that are installed for fire brigade use such as hydrants, brigade communications, and fire fan controls.

All long road tunnels in Australia are managed from an on-site control centre or remotely from a central traffic centre. The designers typically maintain an operator focus. Verification of the tunnel life safety measures always involves peer review by an external expert.

Agnew, in general terms, recommends the following safety measures for tunnels (Agnew, 2011).

- Efficient incident detection through automatic video detection of stopped vehicles and unusual traffic conditions (fast!).
- A fixed fire fighting system (e.g. deluge system) where it is justified (usually in road and bus tunnels longer than 300 m). Typically the deluge system is automatically activated and the tunnel operator can override its activation. Historically, tunnel operators will initiate the fixed fire fighting systems before they are automatically operated. Fixed fire fighting systems are mainly provided for asset protection and so they are seen as cheap business continuity insurance.
- Hydrants in the tunnel and outside the portals for fire brigade use.
- Communication systems to allow the tunnel operator to interact with tunnel occupants.
- Communication systems to allow the fire brigade to communicate with the tunnel operator.

- A smoke management system. One ventilation strategy in longer tunnels is to reduce the longitudinal ventilation to 1.5 m/s during the fire to keep the smoke stratified and the heat release low. Most long road tunnels in Australia have fully transverse ventilation systems (i.e. overhead smoke ducts).
- Hot smoke testing before the tunnel is opened.
- Real full scale training to gain real experience for tunnel operators and fire brigade (e.g. the Sydney Harbour Tunnel burns a real car every 12 to 18 months as an exercise).
- Means of egress. Long road tunnels in Australia typically have cross passages between the tubes. Cross passages can cost several hundred thousand dollars to construct and fit out. Cross passages are normally separated by a distance of 120 m. Long bus tunnels may be provided with egress passages to the side of the tunnel and exit doors spaced every 40 to 60 m.

5.2 The Netherlands

In this section interviews with Thijs Ruland and Twan Daverveld from Royal Haskoning and Ronald Mante at the Dutch Ministry of Infrastructure and the Environment are presented. For realising complex infrastructure projects, The Netherlands have adopted a system engineering (SE) approach originally developed by NASA and Department of Defence in USA. SE is a structured engineering method to structure the engineering and design process. Validation (are we building the right thing according to the road users need?) and verification (are we building it right; are all specifications correctly implemented?) is part of the SE process.

Theoretically safety is verified through a QRA and a scenario analysis³. Lately there have been much public debate about how to arrive at a required safety level and how to prove it. The Netherlands have a minister for Infrastructure and the Environment that is responsible for the legislation on tunnel safety. First the viewpoint from safety consultant Thijs Ruland and Twan Daverveld, Royal Haskoning is presented and then the views of, Ronald Mante and some of his colleagues at the Dutch Ministry of Infrastructure and the Environment are presented.

5.2.1 Thijs Ruland and Twan Daverveld, Royal Haskoning

Thijs Ruland and Twan Daverveld, Senior Consultants, Planning & Transport, have several years of experience from tunnel safety. They explained the approach of Royal Haskoning and The Netherlands to derive, specify, and verify safety (Ruland and Daverveld, 2011). In The Netherlands safety is presently verified formally through a QRA using a standard program and through a scenario analysis. However, Ruland and Daverveld underlines the importance of considering both *people and function* together. Functions are fulfilled, in general, by both technical systems and organisation (e.g. people and procedures). Two main goals are safety and traffic availability, and there is a constant trade-off between these two goals.

5.2.1.1 Functional approach to tunnel safety

The Netherlands takes a very functional perspective focusing on what function the tunnel should have and next try to verify and validate the designed solution in an iterative manner. Below is an example of a tunnel's safety functions expressed by a hierarchical tree structure. Firstly the top objectives are presented in Table 2 (Ruland and Snel, 2010):

³ This was in accordance with the law on tunnel safety in 2011, at the moment (2012) the parliament is discussing a change in the law with no compulsory scenario analysis.

Table 2 The top objectives for validation of designed solutions in The Netherlands (Ruland and Snel, 2010).

Process	Objective
Traffic management	The safety provisions are aimed at a safe and steady flow of traffic and an 'as good as reasonably possible' prevention of incidents and response to disruptions in traffic.
Incident control	The tunnel system has educated and trained personnel and adequate, reliable (technical and organisational) facilities to minimise the consequences of incidents.
Self-rescue	The available safe egress time (ASET) is sufficient for people who are able to get themselves to safety.
Emergency assistance	Emergency assistance can be given effectively.

Each top objective is then divided into lower level sub objectives and functional requirements:

“From the top safety objective ‘Self rescue’ [...] the sub-safety objective ‘Minimisation of the consequences’ can be derived. One of the sub-objectives will be ‘To provide a physical safety escape route’. The associated safety functions are for example ‘Providing sufficient orientation possibilities’ (installations such as tunnel lighting and escape route lighting fit in here), ‘Guidance for people’ (installation solutions can be escape route lighting, signs and audio guidance) and ‘To control the en-route conditions’ (to be fulfilled with ventilation and overpressure but also maintenance procedures to keep routes free of obstacles) (Ruland and Snel, 2010)”

5.2.1.2 Scenario analysis

In the bow tie model of causes and effects, the scenario analysis focuses on managing the effects, or consequences given that a certain plausible event has occurred. Therefore, in the bow tie model the analysis focus on the right bow.

Scenarios more likely than $1 \cdot 10^{-6}$ shall be managed. Less likely scenarios are treated according to the ALARP principle, i.e. the remaining risk is accepted. Selected scenarios are discussed through time steps by experts. Input is the tunnel including all technical and organisational safety measures. During the analysis the experts look at the development of the scenario and check and make notes of the status of several parameters, such as the status of technical systems.

The criteria for the scenario analysis are specified in a report on Dutch for tunnel risk analysis (page 14) (Arbouw et al., 2006) The scenarios can be picked from another Dutch standard. For the scenario analysis soft criteria are used (i.e., not necessarily numerically measurable or Specific, Measurable, Attainable, Relevant and Time-bound (SMART)) (Ruland and Daverveld, 2011)

5.2.1.3 Integrated functional design approach

Royal Haskoning have an innovative design approach to ensure that function and safety are both delivered and optimised. Focus is on validation (did we build the right thing) and verification (how is the practical function). For each iteration in the Systems Engineering (SE) approach, reliability, availability, maintainability and safety (RAMS) are considered. According to Ruland and Daverveld, it is important that the goal is not to use SE but to construct a safe tunnel. It gets very cumbersome otherwise. The use of RAMS induce a constant compromise between safety, maintenance, availability and costs, where the goal is:

- low maintenance,
- high safety,

- high availability, and
- cost efficiency.

Top objectives and derived sub objectives form the basis of functional requirements. Functional requirement could for example be for the rescue service to escort all people who are trapped in a temporarily safe place. Functional requirements, safety systems and procedures (management) are graded in three categories: important, desirable and ‘nice to have’ in a table. The following scenarios may be used in order to prioritize:

- car stops,
- lost item on the road,
- traffic congestion,
- crash,
- fire,
- boiling Liquid Evaporating Vapour Explosion (BLEVE), and
- toxic release.

Toxic release and BLEVE have an likelihood of occurrence below $1 \cdot 10^{-6}$ and do not have to be fully dealt with. The scenarios are run against the tunnel safety systems in a “Swim lane model” to optimise the installation and the processes. The swim lane model starts with the scenarios. Each scenario is time-sequentially stepped through with all stakeholders in a swim lane like table. Each stakeholder have a swim lane in which, at the right sequence in time, he indicates his actions. This facilitates and improves the incident management. Another result is that the function and availability of the tunnel tube is known at the different stages.

Table 3 Swim lane model for the scenario “fire in a car”. Each stakeholder, for example operator and ambulance, indicate what they do for different time points during and after the incident.

Scenarios	Technical systems	Operators	Ambulance	...etc.	Function of tunnel	Time line
“fire in a car”					Green=open	before accident
					Red=stopped	during accident
					Yellow=limited availability	after accident

The swim lane model reveals what each stakeholder need and what we should design. The approach also helps each stakeholder to see, clarify and customize his needs in coordination with all other stakeholders. For example it was found that the fire brigade wanted to have a CCTV signal from the tunnel in the fire truck to know what was happening inside the tunnel and where while approaching the tunnel (Ruland and Daverveld, 2011).

Based on the ISO 15288 (Systems and software engineering – System life cycle processes) and IEC 61508 (Functional safety of electrical/electronic/programmable electronic safety-related systems).the approach to tunnel safety from Royal Haskoning contain no less than 11 different steps. Unfortunately, there was only time to look at a few, however, the method was presented at ISTSS 2012, see (Ruland et al., 2012).

5.2.2 Ronald Mante et al., Rijkswaterstaat (RWS)

Ronald Mante, manager for RWS Centre for tunnel safety, and several of his colleagues gave a series of interesting presentations (Mante, 2011).

According to Mante, other safety models and techniques are not complementary to the QRA and the scenario analysis, but merely supportive. They are used to verify and validate the input data that are used in the analyses. The Verification and Validation scheme is as follows:

1. demonstrate that the safety criteria are met (using QRA and scenario analysis),
2. demonstrate that the input data and starting points are correct / viable,
3. demonstrate that the tunnel system design matches with the input data and starting points, and
4. demonstrate that the built tunnel system matches the design and meets the demands that the design was based upon.

There has been a public debate in the Netherlands focused on the safety criteria mentioned at step 1. Especially the criteria that are used with the scenario analysis leave much room for interpretation, since they have a qualitative nature. In general the QRA focuses on the total risk profile, that is, the summed up risk of all the possible calamity scenarios, and the scenario analysis focuses on minimizing the risk for each separate scenario that is analysed. This results in a discussion whether supplementary safety measures are needed if the safety complies with the QRA-criteria, but the scenario analysis shows that the risks are not totally excluded (which is always the case, of course).

This discussion is possible since the safety criteria are not anchored in the Dutch legislation (but the use of QRA and scenario analysis as instruments for risk analysis is prescribed by law). At the moment, a new proposal for the legislation is offered to the parliament for approval. In this proposal the QRA criterion for the societal risk ($0,1 / N^2$ per kilometre tunnel bore per year) is proposed as the legal norm for tunnel safety. This means that the scenario analysis will no longer be a legal instrument for risk analysis. Mante expects the new legislation to become active in the second half of this year. Of course, the parliament can decide for some changes to be made in the proposal, so Mante is very curious what will happen in the process (Mante, 2011).

5.2.2.1 Systems engineering design process

Since RWS has about 300 contracts per year which they coordinate, e.g., the building of a tunnel represents one such contract. RWS has rather recently started to use SE as a working method to administer the contracts. RWS and the contractors cooperate closely through the SE philosophy. The first step of basic project management according to the SE philosophy is viewed as fully learned. The current step in the developing chain is the verification and validation process. In the following sections the RWS SE method is briefly described.

5.2.2.2 Specifications

It is very important according to the SE philosophy, to clearly and accurately specify what the system is, does, and should handle. According to Mante there are three sorts of specifications: stakeholder requirements, system specifications and demand specifications. Safety is guaranteed through applying RAMS and verification plus validation of functionality and specifications for each subsystem or component. Top level specifications (safety and availability) and bottom level system are easy to specify. The difficult process is in between: to go from top level requirement to each specific system, and to define all the processes involved, such as closing a tunnel for example.

5.2.2.3 Verification and validation (V-model)

The specification process is iteratively going into finer and finer detail closely connected to the design or solution (**why**) process, the design aids in formulating the requirements (**how**) at lower level. During the design process specifications are becoming more and more detailed. This is illustrated in a standard for RWS projects and the use of SE, see Figure 3 and 4.

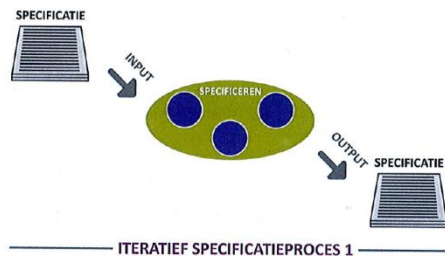


Figure 4 Evolvement of specifications: going towards more and more detail (RWS, 2011).

Eventually, the specification is detailed enough to start the realisation. Each specification step is validated and verified as the design is being realised, from smaller components to larger system parts. As can be seen in Figure 5, a “V” is then formed.

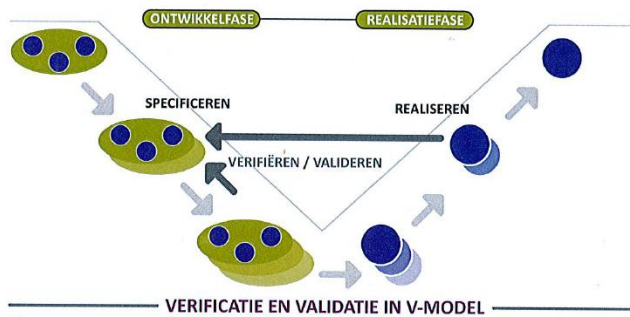


Figure 5 The V model verifying and validating the realised design with corresponding specification at each level of detail (RWS, 2011).

Using a SE approach, it is clear what each subsystem (object) is performing (the specification is known) and what functions (specifications were derived from functions) it fulfils as can be seen in Figure 6.

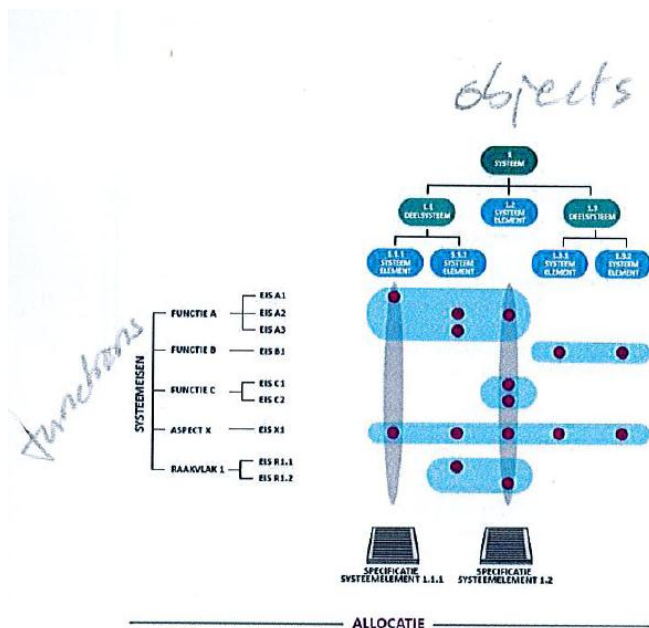


Figure 6 Holistic view over the connection between tunnel objectives, functions and system specifications (RWS, 2011).

5.2.2.4 Failure definitions

Including RAMS in the SE process has led to the development of failure definitions for each system or safety function covering:

- availability:
 - failure frequencies for tunnel systems (reliability),
 - maintenance (there will be several scheduled maintenance windows per each year for the tunnel and for each subsystem the maintenance window is specified), and
- safety:
 - operational measures (e.g. light system failure can be treated either ,through reducing the speed limit and repair later, or through immediate repair without taking any additional safety measures).

For each safety function and its degraded functionality different repair priorities are allocated to the failing systems, depending on the extra risks the failure introduces for the road users, see Table 4.

Table 4 Example of failure definitions for a tunnel’s safety systems and functions.

Safety function	Failure def.	Measure to detect failure	Consequence of failure	Repair priority (without measures to reduce extra risks)	Possible measures to reduce the risk	Repair priority if measures are taken in practice
E.g. Lighting system	When is the functionality achieved? E.g. to what degree can the entrance lighting of the tunnel fail before safety can no longer be maintained on the required level?	E.g. optical sensor	Description of extra risks for road user due to failure	4 repair priorities	E.g. reduce speed	E.g.: priority decreases from 2 to 4 if speed is reduced

The four repair priorities are:

1. immediate danger: close down,
2. repair first night,
3. repair within one week, and
4. repair in next maintenance window.

The column ‘consequence of failure’ explains which safety level the tunnel is degraded to if the safety function in the left column is unavailable. The column ‘Measures to reduce the risk’ indicates which options are available to increase the safety level even though the safety function is still unavailable. To illustrate with an example: the failure definition for the lighting system is to provide a minimum amount of light per unit area at all spots in the tunnel. If this is not met safety might for example be reduced to level one, i.e., close the tunnel, however, taking an extra safety measure to reduce the speed might increase

the safety level to two which means the tunnel may be kept open if the lighting system is repaired during the first night. Two years ago this was not highlighted at all. Neither were there any guidelines for tunnel operators what to do. Today measures and guidelines exist and the tunnel operators are very happy to now know what to actually do when systems fail (Mante, 2011).

5.2.2.5 Critical safety functions

At the time of the interview all systems or tunnel functions were assigned a Safety indicator level (SIL). SIL is defined as a relative level of risk-reduction provided by a safety function. In the IEC 61508 standard four SILs are defined, with SIL 4 being the most dependable and SIL 1 being the least. A SIL is determined based on a number of quantitative factors in combination with qualitative factors such as development process and safety life cycle management. SIL is used in order to optimize the tunnel maintenance, availability and function during normal operation.

Recently, however, RWS have decided not to apply SIL-levels (i.e. IEC-61508 is not applied), instead RWS specify reliability demands for the systems, based on the risk reduction factors and matching the reliability level that one would expect if the SIL-level derived from the risk reduction factor was applied. The difference is, that RWS apply fault tree analysis to demonstrate that the reliability demands are met, rather than to organize the development process according to the IEC-standard whereby the realized reliability is assumed because a controlled process was followed.

RWS use the Task Oriented Probability of Abnormalities Analysis for Software (TOPAAS) instrument to demonstrate the software reliability, which is used as input in the fault tree analysis.

To summarize.

- RWS use the failure definitions to derive the reliability demands to meet the availability top demand for the tunnel.
- RWS use the risk reduction factors for the reliability demands from the safety point of view.
- The most severe demand for reliability (derived from availability and safety) is applied.

5.2.2.6 RWS QRA model

The top objective for a tunnel is the criterion for societal risk according to RWS. This criterion is verified through using a QRA model which RWS have developed for assessing the risk in tunnels. The computing model considers $0.5 \cdot 10^6$ scenarios. The following parameters are the RWS QRA input for each tunnel:

- geometry,
- safety features, for instance:
 - operator,
 - ventilation,
 - loudspeakers,
 - fire extinguishing equipment,
 - communication equipment,
 - fire detection,
 - emergency button in the operator room (makes many things at once),
 - tunnel closure (traffic light or boom?),
 - Ventilation starts automatically at fire detection or not,
- traffic intensity,
 - traffic composition,
- number of people per vehicle,

- traffic jam, and
- incident probabilities.

Only a limited amount of fire simulations has been performed for fire sizes 5, 10, 25, 50 and 100 MW (in all cases: with and without ventilation). The result is used in all QRA simulations. Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) are used to estimate fatalities.

The criteria is not hard, in the sense that, a debate is possible if the FN-criterion is not fulfilled. The modelling focuses on the cases/zones: 1) accident zone, 2) people trapped in vehicles downstream and 3) all other vehicles upstream.

Table 5 Quantitative risk criteria used in The Netherlands.

Type of risk	Risk criteria for road tunnels
Individual risk per travellers km	$1 * 10^{-7}$
Societal risk per km per year	$0.1/N^2$

Experience shows that the added risk from fires and toxic releases is so small, in terms of individual risk, that it does not influence the individual risk measure since it is dominated by traffic incidents. Therefore RWS want to use only a societal risk criterion, for which risks from fires and toxic release are significant.

The model is not capable of simulating sprinkler, however, you can choose to set that the fire is extinguished in 99 % of the cases. Toxic release, BLEVE and highly flammable stuff are by default not extinguished by sprinklers. The model shows that these are the substance leading to fatalities. Compared to the distance between escape doors, sprinklers are not effective. Furthermore, the service of a sprinkler system is one day per year which is larger than the expected increase in availability due to sprinkler suppressed fires (Mante, 2011).

5.2.2.7 Scenario analysis

The Dutch scenario analysis is explained in the PIARC section: 2.4.

5.2.2.8 New approach

After iterating several tunnel designs, subsystems and functions and seeing the same discussions and arguments over and over, RWS have found that some 85 % of all design decisions end up the same. Therefore they want to make these 85 % prescriptive and leave the 15 % to be variable. They want to base the design on a standard tunnel, which is now available, and will be prescribed for state owned road tunnels in the new legislation. Analysis has shown, that the measures included in the tunnel standard are sufficient to meet the societal risk criterion with all the existent and planned tunnels in the Netherlands. The tunnel standard is therefore robust. If in the future a new to be built tunnel doesn't meet the criterion with the tunnel standard, supplementary measures are to be taken until the criterion is met.

5.3 Georg Mayer, PTV, Germany

Dr. Georg Mayer work for PTV in Germany (Mayer, 2011). PTV AG is a consulting company focusing on the three business fields Traffic Software, Transport Consulting and Logistics Software. In Germany safety is mainly verified through compliance with prescriptive guidelines, although the guidelines allows a risk-based approach for certain cases (PIARC, 2008). Dr Mayer has now performed several QRA for tunnels in Germany. The QRA used today is an in house development at PTV. It is based on FDS for simulating the fire. Three scenarios with fire sizes 5, 30 and 100 MW are used. Standard Eurocode fire curves are used to model the fire development. Both a high and a slow fire growth rate are used. The slow fire growth rates pose a challenge for the

detection system. Current challenges include adding a social model to be able to simulate the human behaviour for each individual road user.

RABT 2006, the German tunnel standard, is mainly prescriptive. There is no criteria defined for societal or individual risk. However, there are tenability criteria for road users. For example, the visibility should be at least 5 m during fire. Therefore, the output in terms of societal risk is often compared with a reference “standard” tunnel. Mayer is unsure whether the risk is normalised per km, but believes it is not. This implies that the calculated risk likely is larger for a longer tunnel than a short one. Mayer would prefer if a fixed criterion for societal risk (FN-curve) would be defined for Germany. In general, today, each safety system is evaluated separately.

In Germany the fire brigade sometimes wants to install sprinklers, but the German traffic administration wants to have clear evidence on the net benefit from sprinkler systems before making any decisions. The view on the benefits from sprinkler is in Germany (as in most European countries) overall ambiguous (Mayer, 2011).

6 Discussion

In this chapter critical aspects are analysed and the foundations for a future tunnel standard are outlined.

6.1 Discussion and limitation of the interviews

Based on the three interviews with experts from Australia, see section 5.1, we conclude that Australia is building tunnels with a very high safety level. From a socio-economic point of view, however, this is not necessarily the best solution. The design process requires many stakeholders to participate, each stakeholder's requirements for safety are taken seriously and are likely implemented due to the strong public and legal requirements on stakeholders involved concerning safety. It is good that stakeholders are involved since this legitimates decisions and the process, see section 2.5. However, as Sweden has a different political and legal climate, it may be that a similar process in Sweden would have a different outcome. A process such as the one in Australia requires a great deal from the stakeholders, e.g. they must be up to date with tunnel safety. However, should there not be any clear view of what constitutes a safe tunnel among the stakeholders, the process might only display different point of views without being able to arrive at common conclusions. Based on the interviews and previous knowledge Australia has a positive experience of sprinklers in tunnels which has led to consensus concerning their adoption. Without this consensus a stakeholder dialogue could lead to locked positions and significant disagreement.

Based on two interviews, see section 5.2, the Netherlands have many interesting models and concepts to structure the design and engineering process and to validate and verify safety which should increase safety through identifying weak spots, provide training and improved, clear procedures.

The positive experience from sprinklers in Australia is in contradiction with the conclusions drawn by the Netherlands and RWS from the simulated RWS QRA output where they find that sprinklers are in relation to the distance between emergency doors not efficient. In fact, the sprinkler system yearly maintenance cost more, in terms of tunnel availability, than the estimated increased availability from having the system. The impression given from RWS concerning the predictability of the RWS QRA model is that it would be very close to reality. However, given the assumptions concerning fire dynamics and fire suppression and that it has not been validated against real data it is questioned whether the RWS QRA output can be used to draw general conclusions concerning the usefulness of sprinklers.

From Germany, only one person was interviewed which makes it hard to draw any general conclusions, however the interview confirmed prior knowledge that Germany has a similar situation to that in Sweden, i.e.: there are no numerical risk criteria defined, tunnel systems are evaluated separately, and sprinklers are in general not installed. A remark based on this particular interview concerned the societal risk output (FN-curve) which we think should be normalized per km and per vehicle. Likely a long and/or highly frequented tunnel should also have an increased benefit. If the societal risk output (FN-curve) is per tunnel it would mean that very long and/or highly frequented tunnels are impossible to "make safe enough", simply just because they naturally have a higher risk compared to a less frequented or shorter tunnel.

One limitation of the interviews is that they only cover a limited set of personal opinions. Albeit it is one of few ways to get the latest practice which is in use today, the result should not be generalised, but reflect the opinion of that expert or group of experts. The interviews should not be compared since they were conducted following a semi-structured interview method, the number of interviewed was statistically low, the

profession of the subjects interviewed differed, and the questions were not exactly the same.

6.2 Foundations for a new tunnel standard

In this section the various parts presented in the report will be connected in a framework of how a future design standard could be structured.

It is a basic starting point to define the problem, and to acknowledge that perhaps not all objectives or prescriptive requirements from the past need to be included today in a new performance-based code. The real purpose behind the prescriptive rules need to be found (Almgren and Hansson, 2010). However, a “deemed to satisfy” solution (more or less the same as prescriptive requirements) would help since this would imply what is acceptable (Almgren and Hansson, 2010).

Starting with the safety circle, the bow tie model and the general framework presented in the PIARC report concerning road tunnel safety (see section 2.2), many perspectives of the safety issue are addressed. Their general framework, therefore, appears to be a beneficial starting point, i.e.:

1. Safety level criteria specifying desired level of safety
2. Infrastructure safety measures involve the technical systems and instruments, geometrical and structural solutions and materials used in all parts of the tunnel
3. Operational safety measures include procedures for adequate tunnel safety management
4. Socio-economic and cost-benefit: how to do the trade-off between high quality and reliability in terms of safety versus cost effectiveness
5. Safety assessment for verification of tunnel safety
6. Knowledge of road tunnel usage: re-asses safety should the traffic flow or characterisation change more than previewed
7. Stage of the tunnel life affect the detail of a safety analysis
8. Using operating experience
9. Tunnel condition: assure the intended function

All points are more or less connected to each other and no single one can really be addressed separately. Therefore it makes sense to view them in a tunnel life cycle perspective. This is also what was done in the PIARC report. The four phases used by PIARC were planning, design, construction and operation. In this sense information, safety assessments and criteria will be used on various levels: starting on a high level in the early planning phase, drawing the rough design, identifying stakeholders, etc. Towards the end of the design phase, details and criteria have narrowed down into detailed specifications.

Safety and function is a vital part in each step. In fact this is very similar to the approach to tunnel safety used in The Netherlands. Through the use of systems engineering (SE) the design is iterated into more and more detail (see section 5.2). In each iteration step the design is validated and verified. Furthermore, RAMS (reliability, availability, maintainability and safety) should guide the process in an optimal way. However, the use of SE is to a large extent a two way process which means that both STA and engineers would have to adopt an SE working method. Otherwise there would be no validation of the process (see the V-model, section 5.2.2.3) which means the end product would not necessarily match with the intentions.

A less ambitious approach would be to specify the system in the SE way once and for all so that the logical process from planning (rough specification, high level criteria) to design (detailed specification, also including low level criteria) could still be followed.

That is, the requirements in the future design standard could be structured in such a way, that high level and low level requirements easily can be identified. Looking at the Netherlands again, the tree structure developed by Ruland and Snel suits this approach very well (see section 5.2). From a high level to a low level, top safety objectives (high level) are expressed in a tree, down to lower and lower specifications (functional and prescriptive criteria). In this tree structure RAMS can be iterated for each node which would be a very similar approach to SE but somewhat more simple. Also note that The Netherlands have actually started to realize they are using the same arguments over and over in the specification process. Therefore, they intend to standardise some 85 % of the design parameters since the result in these cases always is the same. Bearing this in mind Sweden could start from here leaving only some key aspects open for performance-based design.

As can be seen from both Australia and The Netherlands, the early inclusion of stakeholders is vital for the process. Stakeholders should be involved in the process outlined here to construct a new design standard. In Sweden we know that the role of different stakeholders is rather unclear. Their role in future projects should be made explicit in terms of participation and the level of involvement. Who is to be regarded as expert in which fields and who will have more of an advisory role and when? A key question concerns safety decisions in various stages during the working process. Preferably a discussion of the desired safety level is done at an early stage including key stakeholders with a give and take mentality. It is important to define criteria for acceptance and methods for showing compliance together at an early stage.

Systems often depend on each other, e.g. operator central, CCTV, traffic and incident management, deluge sprinkler system and fast response, strongly depend on each other. The functional reduction in removing the operator who is central in the example would be immense. Many of the other system directly or indirectly depend on the operator. Furthermore safety engineering has some good concepts to contribute, such as reliability analysis, inherent safety and fail safe design.

As was stated by both PIARC and Australia it is important to consider safety in all stages of the tunnel process. During planning, design and when operation scenario analysis are performed. In the planning phase stakeholders are identified to participate in the scenario analysis, scenarios are selected, general principles and criteria for ensuring safety are identified. In the design phase a more detailed scenario analysis is performed also taking consideration of the function of each safety system. In the operation phase a scenario analysis is performed periodically including the operators. Focus in the operation phase is to train and tune the emergency response.

Since RAMS are performed for each considered tree node, reliability, availability, maintainability and safety are specified for each specific system and tunnel functional requirement. These specifications are used and stress tested in the scenario analysis. Note that in Sweden the working process is quite different from the process outlined by PIARC, for example the planning and design process (“Projekteringsprocess”) consists of the following four stages: prestudy (“förstudie”), road planing (“vägutredning”), work plan (“arbetsplan”), and construction plan (“byggplan”).

Result from the RAMS and scenario analysis are collected in two documents: (1) the emergency response plan which is for all stakeholders concerned with the emergency response and clearly states who makes what and when and includes previous learning and future improvements of the plan; (2) the operation instructions which are primarily for the tunnel owner and operating unit. The operating instructions specify periodic maintenance and testing plans, tunnel availability as a function of reduced function and measures to take to ensure satisfactory safety.

There are upper limits on what tunnel safety can cost and the benefits are also different for each specific case. It will not be clear, and cannot be clear what makes a tunnel

satisfactory safe in general. However, certain guiding principles, laws, safety on roads in general, and economy can guide the decision in the right direction for each specific tunnel.

In (Beard and Cope, 2007) the minimum requirements for a design methodology (including risk analysis) are stated as:

- *“Encourage the user to be explicit and make all assumptions crystal clear.*
- *Iterations needs to be part of the process.*
- *Incorporate explicitly a capacity to learn from previous incidents (both serious, minor and near misses).*
- *Allow for different kinds of models to be employed: physical, qualitative and quantitative.*
- *Precautionary (uncertainty whether there is a real threat) and cautionary (when there is a significant threat) principles should be given due considerations.*
- *Systematic safety management system (Beard and Cope, 2007, p.11).”*

These criteria can therefore be seen as aims or boundary conditions in the process of designing a future design standard.

Generally much focus of today's tunnel safety is on mitigation and intervention, considering the safety circle, easy safety improvements might be obtained through looking at other areas of the safety circle, in particular on pro-action and prevention. Future research could aim at these areas.

7 Conclusions

The overall conclusions of the study presented in this report are as follows.

- Fire safety in tunnels can be specified by a combination of:
 - prescriptive requirements specifying how to do,
 - specification of scenarios to handle, either defined in a standard or by relevant stakeholders on a project basis, and
 - functional requirements and objectives specifying what the tunnel should handle.
- Suitable tools for validation and verification of fire safety exist:
 - interactive and practical scenario analysis with emergency organisation,
 - scenario risk analysis by engineers and designers,
 - international safety standards and procedures,
 - systems engineering ideas to structure the engineering process, and
 - safety concepts, e.g. RAMS, safety circle, bow tie model.
- Safety should be considered from all aspects of the safety circle: from pro-action to after-care and evaluation (learning).
- A challenging part is to consider safety during the whole process and to have a good engineering structure and workflow. PIARC define the following phases: planning, design, construction and operation. Safety must be considered in all phases and information needs to be passed on and reassessed. All steps should be verified and validated against previous steps to ensure that we are building what we intended to and that it really works in practice as was intended.
- Concerned stakeholders should create the overall framework for the process and key safety decisions, and be included in the right phase according to his or her knowledge and role.

8 References

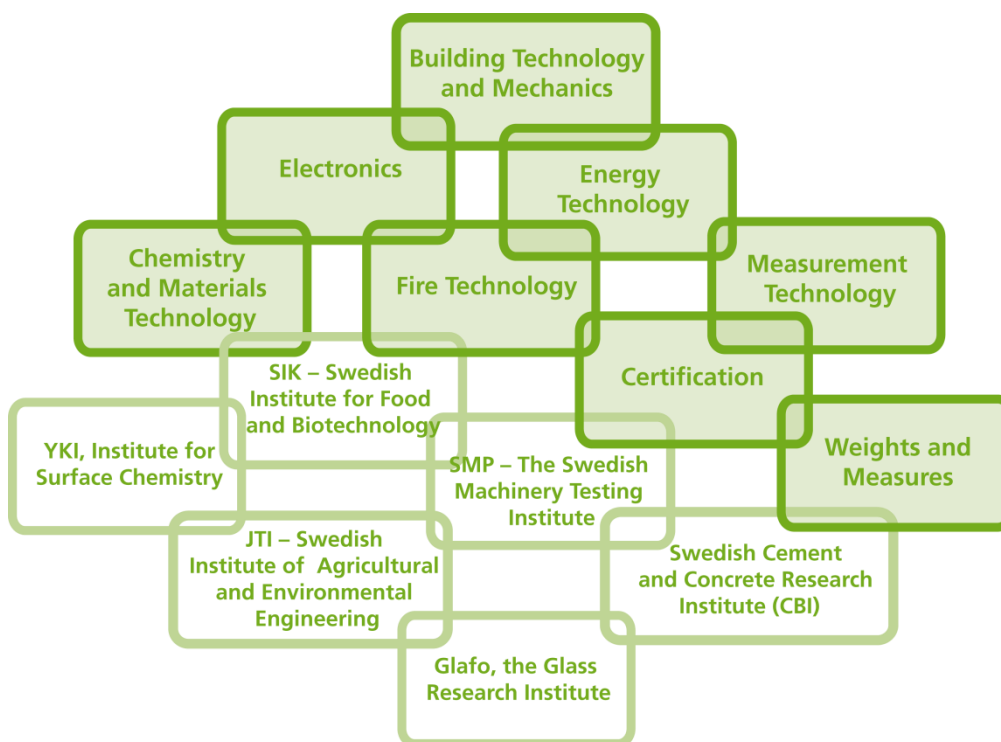
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