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Fire safety design of road tunnels

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Fire safety design of road tunnels

The increasing construction of city road tunnels, the alpine accidents and the following EC directive has placed road tunnel fire safety high on the agenda. However, modern unidirectional road tunnels are often among the safest parts of the road system. Have we come to a point where resources are better used elsewhere? This leads to a central question of this thesis: how safe is safe enough? Along the way, this turned out to be a very challenging and intriguing question. In literature it emerges in different framings and consequently different logical answers.

Along the way questions such as what fire safety is, how it can be measured, whether we are posing the right questions, or engineer the best solutions, have arisen. Throughout this work, the focus has been on road tunnels. Tunnels are hard physical and technical systems. However, they exist in a social reality and a complex society. During the design process many social and soft issues surface that can conflict with technical fire safety measures. The proposed problem framing thus acknowledge both the scientific or technical aspects of risk and social structures; the ethical and democratic aspects of risk, in a decision-making framework. This emphasizes how the problem is framed, what our objectives are, and how creative alternatives are generated and assessed.

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Fire safety design of road tunnels

Jonatan Gehandler

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Abstract
This thesis can be described as a journey in performance-based fire safety design. Along the way questions such as what fire safety is, how it can be measured, whether we are posing the right questions, or engineer the best solutions, have arisen. The safety journey naturally started out with the traditional view, with fire safety engineering based on limit-based design. Using this paradigm the safety problem is limited to fire safety issues, and safety levels are defined for each fire safety objective in isolation. This contradicts the basic rationale of decision-making where the best trade-off is sought between all objectives, most often by use of Cost-Benefit Analysis (CBA). This naturally led to the second stop of the safety journey called CBA-based design where risk is exchanged as a cost factor in a cost-benefit framework. In this paradigm safety is a relative concept depending also on a few other measurable objectives. Throughout this work, the focus of the journey has been on road tunnels. Tunnels are hard physical and technical systems. However, they exist in a social reality and a complex society. During the design process many social and soft issues surface that can conflict with technical fire safety measures. The journey thus went on to acknowledge both the scientific or technical aspects of risk and social structures; the ethical and democratic aspects of risk, in a decision-making framework. This emphasizes how the problem is framed, what our objecitvies are, and how creative alternatives are generated and assessed. It may not even be relevant to talk about "how safe should the tunnel be" because it is subordinate to the overall decision condition, all aspects considered. In the end a design alternative is chosen that exhibit the highest utility on all objectives together, i.e. safety in balance with other objecitves. For any tentative design, safety can develop in two directions; Firstly, it may be that some safety measures are too conservative or in conflict with other objectives such as cost or the environemnt, i.e. resources are better used elsewehere. Secondly, it may also be possible to achieve more safety; it is argued that a Vision Zero design philosophy with its emphasis on inherently safer or fail-safe systems highlight important safety qualities which are not highlighted in limit-based or CBA-based design. Along the way (a) road tunnel fire safety and risk literature were studied, (b) interviews were made with with tunnel fire safety professionals (c) performance-based requirements for road tunnel fire safety were derived, (d) the accuracy of tunnel fire dynamics models applied in road tunnel fire risk analysis was compared with experimental data, and (e) the design framework of fire safety engineering was critically analyzed and an alternative fire safety design framework was proposed.

Key words
Road tunnel fire safety, fire safety engineering, design framework, risk evaluation.

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Fire safety design of road tunnels

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Till pappa och mamma

The woods of Arcady are dead,
And over is their antique joy;
Of old the world on dreaming fed;
Grey Truth is now her painted toy; — William Butler Yeats

Beauty will save the world — Fyodor Dostoyevsky

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I sincerely wish to express my gratitude to my main supervisor Adj Prof Haukur Ingason and my supervisors Adj Prof Anders Lönnermark and Dr Kerstin Eriksson at RISE Research Institutes of Sweden. Thank you so much for giving me so much feedback repeatedly, despite that the expectations in later revisions was not always met. Thank you also for bearing with me in lengthy discussions we have had on various issues. I would also like to thank my former main supervisor, Dr Håkan Frantzich at Lund University (LU). Thank you for giving me a good start into the subject of fire technology and risk management. Thank you also for very valuable comments on a later revision of this thesis. Finally, but not least I would like to thank Dr Håkan Frantzich, Prof Patrick van Hees and Prof Margaret McNamee at LU for their engagement in finalizing this work.

I would also like to thank Dr Francine Amon and Prof Margaret McNamee for English proof reading, thank you so much for your constructive comments and time!

I would also like to thank interviewees for the interviews.

Without the support and love from my parents and grandma this thesis would never have been undertaken, therefore it is dedicated to them. Finally, thanks to my always supporting and understanding dear wife and children. Thank you all!

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Jonatan Gehandler

Borås, 2020

Populärvetenskaplig sammanfattning

Detta är en akademisk avhandling inom ämnet brandteknik framlagd vid en disputation för doktorsexamen. Avhandlingen består av en sammanfattande introduktion (kallad ”kappa”) och fyra vetenskapligt granskade artiklar publicerade i internationella tidskrifter. Kappan innehåller även teori, metod, en resultatsammanfattning, ett förklarande exempel, en diskussionsdel och slutsatser.

Den första svenska vägtunneln byggdes först år 1958 och går genom en bergsknalle på Orust i Bohuslän. Tunneln är knappt 80 meter lång. Sedan dess har antalet vägtunnlar, deras längd och komplexitet ökat, inte minst på senare tid i större svenska städer. Tunnlar kan bidra till att lösa trafikproblem och ta bort stora vägar ifrån stadsbilden. Vägtunnlar som byggs idag i Sverige består oftast av två tunnelrör. Trafiken är då enkelriktad i varje tunnelrör. Efter miljötragedin i Hallandsåstunneln och de allvarliga tunnelbränderna i Europa 1999 och 2001 i enkelrörstunnlar i Alperna med mötande trafik, har tunnelsäkerhet blivit ett högt prioriterat område.

Som en följd av de tragiska bränderna i Alperna initierades europeiska forskningsprojekt och 2004 utkom ett EU-direktiv med minimikrav för tunnelsäkerhet. Enligt EU-direktiv (2004/54/EC) om minimikrav för säkerhet i tunnlar som ingår i det transeuropeiska vägnätet ska riskanalys användas för att visa att en tunnel är säker nog. Sammantaget har detta lett till en ökad medvetenhet och förståelse gällande bränder i tunnlar. När svenska tunnlar dimensioneras för brand är praxis att brandsäkerheten förbättras, jämfört med tidigare tunnlar. Man kan dock ifrågasätta om inte dubbelrörstunnlar är säkra nog? I Sverige idag har ingen omkommit i en tunnelbrand. Resurser skulle kunna göra mer nytta inom andra delar av transportsystemet eller inom andra områden såsom begränsandet av klimatförändringar. De fyra artiklarna fokuserar på riskanalys, dimensionering och beslutsfattande för vägtunnlar.

Artikel I är en kunskapssammanställning om brandsäkerhet i tunnlar och olika teorier och metoder om risk och säkerhet. Brandsäkerhet i tunnlar är ett litet och smalt fält med en stark koppling till ingenjörsvetenskapen och mer specifikt brandteknik och riskhantering. Risk och säkerhet är ett spännande område eftersom det studeras inom en mängd olika vetenskaper. Detta ger flera olika perspektiv på risk- eller säkerhetsproblemet, vilket i sin tur möjliggör för interdisciplinära sätt att hantera risk eller säkerhet.

En tunnel är ett byggnadsverk och lyder därmed under övergripande regelverk såsom miljöbalken och plan- och bygglagen samt tillhörande förordning. Efter det att EU-direktivet infördes finns också en tunnellag och en tunnelförordning, som i stort speglar EU direktivet. Sedan 1995 har Trafikverket använt sig av tekniska kravspecifikationer för tunnelbyggen. Genom dessa regler och den stora mängden av tunnelprojekt sedan 1990-talet finns det idag regler och praxis gällande hur en godtagbar säkerhetslösning för tunnlar ska se ut i detalj. I projekten görs flera riskanalyser. Riskhantering är en central och formaliserad del i nutida tunnelprojekt. Ingenjörsvetenskaper inom riskhantering och brandsäkerhet har bidragit till en trend att övergå till mer funktionsbaserade regler inom fler olika områden. Med funktionsbaserade regler är det istället funktionen som regleras. Det är då fritt fram att ta fram individuella lösningar så länge funktionen uppfylls. För tunnlar har reglerna ännu ingen funktionsbaserad struktur. I artikel II har ett förslag till funktionsbaserade regler för svenska tunnlar arbetats fram utifrån svenska regelverk och förutsättningar.

Med funktionsbaserade regler behöver man visa att mål, såsom möjligheten till självräddning, är uppnådda. Det man då traditionellt är intresserad av är en riskanalys som visar att tiden för utrymning är kortare än tiden tills kritiska förhållanden uppstår. Kunskap om utvecklingen av bränder i tunnlar har, främst under de senaste 20 åren, utvecklats genom flertalet stor- och småskaliga experiment. Detta har resulterat i en stor mängd ingenjörsformler och simuleringsmodeller som gör att en mängd branddynamikparametrar såsom brandens utveckling och rökspridning kan beräknas. Osäkerheten i dessa formler och modeller om de används i en riskanalys har dock inte utvärderats i tillräcklig omfattning. Artikel III är en empirisk studie som jämför skillnaden mellan teori och experiment gällande tiden tills kritiska förhållanden uppstår. Artikel III visar att, eftersom tunnelbränder i verklighet och experiment utvecklas relativt snabbt, felet mellan de teoretiska modellerna och experiment för typiska utrymningskritiska faktorer blir relativt litet (10–20%). Detta betyder att de undersökta formlerna bidrar med en relativt liten osäkerhet till funktionsbaserad design av möjligheten till utrymning, jämfört med den övergripande osäkerheten i riskanalyser.

Funktionsbaserade regler erbjuder större frihet till ingenjörer och konstruktörer att ta fram innovativa lösningar. Dock kan brister identifierats i den process och det tänkesätt som används inom analytisk dimensionering av brandsäkerhet idag. Ingenjörsvetenskapen dominerar processen vilket ger en matematiskt fokuserad process med fokus på att verifiera relativt godtyckliga kvantitativa mål som anses representera en acceptabel säkerhet. Det räcker som regel att visa att *en* lösning uppfyller uppsatta säkerhetsmål. Eftersom oftast bara en lösning utvärderas kan det ifrågasättas om dagens process leder till att de bästa lösningarna verkligen tas fram sett ut ett beslutsperspektiv där det kanske inte ens är relevant att tala om ’hur säker tunneln ska vara’ eftersom det är underordnat det övergripande beslutsvillkoret, alla aspekter beaktade. Andra mål som vi värnar om såsom kostnad, miljö och rättvisa finns naturligt med som en del i vägprocessen genom miljöbalken men passar inte in i dagens dimensioneringsprocess. Det upplevs som ”svårt” att väga brandsäkerhet mot andra mål. Istället blir principer såsom undvikande av katastrofer och ständig förbättring dimensionerande för brandsäkerheten. Det är inte nödvändigtvis rimligt att brandsäkerhet i tunnlar ständigt ska förbättras, givet begränsade resurser och andra akuta risker såsom klimathotet, som dessutom kan stå i konflikt med en ökad brandsäkerhet. Någon mekanism krävs som ger en balanserad avvägning utifrån dagens samhälle och värld.

Ett nytt ramverk för designprocessen har föreslagits i artikel IV. Ramverket bygger på att problemet formuleras som ett öppet beslutsproblem med målet att hitta den *bästa* lösningen, givet de mål som finns hos inblandade aktörer och lagar i designprocessen. En beslutsmetod med följande steg kan då användas: #1 problemformulering; löser vi rätt problem? #2 vilka mål vill vi att lösningen ska uppnå?, #3 Skapa kreativa alternativ; lösningen kan inte vara bättre än det bästa alternativet!, #4 Vilka konsekvenser har alternativen på målen? Här undersöks hur väl målen uppfylls och vilka osäkerheter som finns, och #5 En värdering av vilket alternativ som bäst löser problemet. Dessa steg upprepas tills beslutsfattarna känner att det bästa alternativet har hittats.

Genom att formulera designproblemet som ett mer öppet beslutsproblem kan fler relevanta perspektiv inkluderas och fler typer av mål sättas upp. Ett exempel på mål som har potentialen att skapa säkrare tunnlar är Nollvisionen. Nollvisionen är mycket mer än det avlägsna målet noll allvarligt skadade och döda. Nollvisionen erbjuder framförallt en filosofi med effektiva strategier för att en dag nå målet. Alla aktörer ska övertygas att bidra till visionen. Ytterst är det de som designar systemen som har ansvaret och inte den föränderlige människan. I bästa fall ska systemet ha en inneboende säkerhet så att det inte kan fela. När fel inte kan elimineras helt måste systemet också vara förlåtande så att allvarliga mänskliga skador uteblir vid olyckor. En enkelriktad vägtunnel med ventilation längs färdriktningen hamnar till exempel i ett förlåtande läge vid brand; fordon nedströms branden hinner köra ut innan tunnelröret rökfylls nedströms branden. Människor och fordon uppströms branden är inte hotade av röken.

Ur ett beslutsperspektiv kan tunnelsäkerhet stå i konflikt med flera andra mål som vi värnar om. Flera faktorer har identifierats som påverkar säkerheten i en tunnel. Brandsäkerhet kan främja och stå i konflikt med miljöaspekter, till exempel utsläpp av växthusgaser. Med ett rättviseperspektiv bör vi prioritera mer sårbara och riskutsatta trafikanter på trottoarer och övergångsställen ovan mark. En god upplevd säkerhet när man kör genom en tunnel gynnar människors frihet samtidigt som det leder till mindre stress och olyckor. Grundtanken inom beslutsteori är att välja den lösning och kompromiss som sammantaget bäst uppfyller målen. Målen och prioriteringen av dem bestäms av byggherren och förvaltaren, ofta Trafikverket, i samråd med andra berörda aktörer och bör svara mot samhällets värderingar. Enbart genom att beakta alla delar av beslutsprocessen kan man garantera att det bästa beslutet har fattats.

List of abbreviations

A	cross-sectional area of the tunnel (m^2)
ALARP	as low ss reasonably practicable
ASET	available safe escape time (s)
CBA	Cost-Benefit Analysis
D_{mass}	mass optical density (m^2/kg)
EC	European Comission
FED	accumulative fractional effective dose
FFFS	fixed fire-fighting system
FSE	fire safety engineering
H_{ec}	effective chemical heat of combustion (kJ/kg)
HGV	heavy goods vehicles
HRR	heat release rate (kW)
LCA	Life-Cycle Assessment
MCA	Multi-Criteria Analysis
MKB	environmental protection assessment (Swedish: miljökonsekvensbeskrivning)
MW	Megawatt, a unit of power equal to one million watts
q''	heat flux (kW/m^2)
QRA	quantitative risk analysis
RO	research objective
RSET	required safe escape time (s)
SFS	Swedish code of statutes
STA	Swedish transport administration
T	air temperature (K)
V	visibility in smoke (m)
X_i	average mole fraction of gas species i over the entire tunnel cross-section

Contents

1 Introduction

Road tunnels are a comparatively new feature in Sweden. The first Swedish road tunnel was 80 m long and was built through a mountain on the island of Orust in 1958. Lately tunnel constructions have multiplied; both in number, complexity, width and length with around 10 % of total road investments being related to road tunnels (Ingason et al. 2009). In this thesis a road tunnel is defined as a tunnel on the road network for motorized vehicles, i.e. pedestrians and cyclists are not allowed in the tunnel. Modern societies naturally strive for increased safety in many areas. Yet risks seem to accumulate at an ever-greater pace. It may be, as Giddens argue, that dangers and threats emerge from the reflexivity of modernity itself (Giddens 1990). In the last decade, around 3000 fatalities occurred in Swedish road traffic[1]. Fires in road tunnels, however, have yet not caused one fatality in Sweden, ever. One may, therefore, argue that Swedish road tunnels are fire safe. Yet, new tunnel projects aim at making road tunnels even safer. One reason may be that western societies are preoccupied with risk management (Beck 1990, Giddens 1990). Another is that severe tunnel fires in terms of lost lives and infrastructure disturbances can happen although they, luckily, are not frequent. Most notably, in Europe, the bidirectional Mont Blanc tunnel fire in 1999 included 34 vehicles and the fire was under control first after 53 hours. The fire resulted in 39 lost lives and a seriously damaged tunnel which remained closed for several years. Due to this and a few other tragic alpine road tunnel fires in Europe in 1999 and 2001 the European Commission (EC) released several research projects and a directive (2004/54/EC) on minimum safety requirements for tunnels on the Trans-European Road Network in 2004. The directive requires that a risk analysis is carried out that take account for design factors and traffic conditions (EC 2004). Following the EC directive in 2004, a Swedish national regulation aimed at road tunnel fire safety was developed. The increased interest into tunnel fire safety has also led to many research projects and ultimately to a tunnel fire safety handbook (Beard and Carvel 2012) and a book on tunnel fire dynamics (Ingason et al. 2015).

The increasing construction of city tunnels, the alpine accidents and the EC directive has placed road tunnel fire safety high on the agenda. However, as is pointed out by Dr Iain Bowman in his keynote at the latest International Symposium on Tunnel

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[1] Swedish road traffic injuries, https://www.trafa.se/en/road-traffic/road-traffic-injuries/

Safety and Security (2018), modern unidirectional road tunnels are often among the safest parts of the road system. Have we come to a point where resources are better used elsewhere? This leads to a central question in the later research of this thesis: *how safe is safe enough?* Along the way, this turned out to be a very challenging and intriguing question. In literature it emerges in different framings and consequently different logical answers. Largely my journey has gone from (1) a limit-based design approach, i.e. safety limits specifying *how safe the tunnel should be*, to (2) a cost-benefit design approach, i.e. *enough safety when the overall utility is maximized,* and finally (3) a decision oriented framing that also includes other factors such as fairness or the quality solutions should have. If we, as most philosophers, should believe the Scottish philosopher David Hume (1711–1776), we cannot derive an *ought* from an *is (Hume 1738)*. How safe something should be is a normative question. Facts and formal analysis are not enough, to say how safe something should be, value judgements are needed. In engineering design projects, there will never be a definite solution, but we can argue for better or worse justification. This thesis will explore fire safety design applied to road tunnels in particular.

1.1 Research objectives

To answer the question, *how safe is safe enough?*, we first need to clarify what road tunnel fire safety is, i.e. what constitutes road tunnel fire safety? In performance-based design, fire safety objectives for the design are specified and verified. Performance-based objectives are not clearly specified in current regulation. Neither is it clear how a performance-based approach should be verified, or how technical trade-offs should be made.

One key Fire Safety Engineering (FSE) objective is that all occupants should be able to escape without experiencing or developing serious health effects, i.e. that the available safe escape time is larger than the required safe escape time. However, such engineering models introduce considerable operational uncertainties (Amendola 1986, Contini et al. 1991, Lauridsen et al. 2002, Fröderberg and Thelandersson 2014). In addition, due to the nature of fire, and our limited understanding of fire and human behaviour, advanced computer models for fire life safety include many assumptions and simplifications (Beard 2005, Beard 2012b). This means that uncertainties in risk analysis of fire life safety are considerable and inevitable. During recent years, tunnel fire dynamics theory based on physics and large and small scale experiments has been developed (Ingason 2012, Ingason et al. 2015). This theory offers an increased understanding of the complex fire phenomena in tunnels. It includes several one-dimensional (1D) hand calculation procedures as a complement to or a replacement of more advanced computer models. However, the tunnel fire dynamics models have not been properly evaluated from a fire risk analysis perspective, i.e. how accurately do they model the time to compromised tenability?

Tunnels are hard physical and technical systems. However, they exist in a social reality and a complex society. During the design process other issues, e.g. social or environmental, surface that can conflict with technical fire safety objectives. Moving forward on our quest for *enough safety*, these other objectives are highlighted. The basis of any risk decision and aim of decision-making in general is to choose the option that promises most of what we want (Hammond et al. 1999). Often this means that trade-offs between conflicting objectives needs to be struck. The theoretical framework of fire safety design is largely based on limit-based design in which fire safety limits are defined for each fire-objective in isolation (SFPE 2007, Bjelland 2013), while the general approach to decision-making is to use a Cost-Benefit Analysis (CBA)-based approach to find the best compromise between life safety, cost and mobility (Elvik 2001, Meacham 2004). From a decision-making perspective, a transition towards CBA-based design offers the advantage that safety can be argued to come at the right cost. However, both limit-based and CBA-based design pays less attention to qualitative and contextual factors, such as problem framing and issues of fairness. Further, they are satisfied with an ‘acceptable’ or ‘safe enough’ solution. If more lives are to be saved with fire safety, other methods are likely more efficient (Babrauskas et al. 2010). The vitality of any field depends on critical examination of its theoretical framework. In this context, the theoretical framework of fire safety design must be examined, and the merits of other design frameworks discussed. For example, Vision Zero that emphasizes inherent safer or at least fail-safe design, sets different requirements on the road tunnel system than those typically analysed and engineered in limit-based design or within the CBA framework. Depending on how the design problem is framed, different design approaches become rational. For example, *how safe the tunnel should be* is in line with a limit-based approach, *enough safety* (in relation to cost) favours a CBA-based approach. How should the design problem actually be framed?

The four topics described above have been reframed as research objectives in this thesis. Therefore, the research objectives (RO) of this thesis are as follows.

RO1	Develop a performance-based design guide for road tunnel fire safety in a Swedish context.
RO2	Investigate the accuracy and applicability of tunnel fire dynamic models for road tunnel fire risk analysis and performance-based design.
RO3	Propose a new fire safety design framework.
RO4	Illustrate different fire safety problem framings with examples.

1.2 Delimitations

This study is mainly focused on road tunnels, but parts of the results will be applicable to other types of tunnels (RO1 and RO2) or buildings (RO3 and RO4). The field of study belongs to fire safety engineering and risk management. Risk is a transdisciplinary field (Renn 1998, Renn 2008). Therefore, answers to many risk problems, e.g. RO3 and RO4 are transdisciplinary.

1.3 Appended papers

This is a compilation thesis including four scientific papers submitted and accepted to scientific journals. All papers have been subject to a full paper peer-review. The following papers are included in the thesis:

Paper I	Gehandler, J. (2015). Road tunnel fire safety and risk: a review. *Fire Science Reviews*, 4(2). doi: 10.1186/s40038-015-0006-6.
Paper II	Gehandler, J., Ingason, H., Lönnermark, A., Frantzich, H., and Strömgren, M. (2014). Performance-based design of road tunnel fire safety: Proposal of new Swedish framework. *Case Studies in Fire Safety*, 1(0), doi: 10.1016/j.csfs.2014.01.002.
Paper III	Gehandler, J., Eymann, L., and Regeffe, M. (2014). Limit-based fire hazard model for evaluating tunnel life safety. *Fire Technology*, 50(4), doi: 10.1007/s10694-014-0406-5.
Paper IV	Gehandler, J. (2017). The theoretical framework of fire safety design: Reflections and alternatives. *Fire Safety Journal*, 91, doi: 10.1016/j.firesaf.2017.03.034.

Paper I II, III and IV are peer reviewed. Paper II, III and IV have also been presented at scientific conferences.

1.3.1 My contribution

In this section I aim to clarify my contribution to the four peer review papers:

Paper I	I conducted the literature review and wrote the paper.
Paper II	The project group (the authors of the paper), with input from the reference group, together developed the design guide. I took a leading role in writing the design guide and the subsequent paper.
Paper III	No experiments were conducted. I took a leading role in model development and supervision of two student works, Ms. Eymann and Mr Regeffe, who made a major part of comparing the model with experimental data. I took a leading role in writing the paper.
Paper IV	I conducted the work and wrote the paper.

1.4 Related publications

The entire performance-based road tunnel design guide covers 90 pages and can be found in the following references:

- Gehandler, J., Ingason, H., Lönnermark, A., Frantzich, H., and Strömgren, M., *Funktionsbaserade krav och rekommendationer för brandsäkerhet i vägtunnlar (FKR-BV12)*, SP Technical Research Institute of Sweden, Borås, Sweden, 2012. [in Swedish]
- Gehandler, J., Ingason, H., Lönnermark, A., Frantzich, H., and Strömgren, M., *Performance-based requirements and recommendations for fire safety in road tunnels (FKR-BV12)*, SP Technical Research Institute of Sweden, Borås, Sweden, 2013. [A shorter version in English]

1.5 Thesis outline

The research work presented revolves around the objective of specifying, measuring and designing fire safety in road tunnels. The next chapter presents the theory and methods used to tackle the research objectives. This is followed by a summary of the results of Paper I-IV. Paper I is a literature review that identifies some challenges and possibilities for fire safety engineering. In Paper II performance-based requirements for road tunnel fire safety and an approach for assessment of compliance is developed. Paper III evaluates the accuracy of tunnel fire dynamic models to predict the time to compromised tenability in risk analysis. Paper IV discuss and proposes a new fire safety design framework. The subsequent chapter, an embryo to a fifth paper, continues from Paper I & IV and applies the proposed design framework in the context of road tunnels. This is followed by a discussion. The thesis finishes with conclusions and future research.

2 Theory

Risk analysis and risk management are leading approaches for managing safety in society today and are also highlighted in the EC directive on road tunnel fire safety. However, as Slovic (2001) points out, billions of dollars have been invested in risk management, but stigmatized risk issues such as climate change, and nuclear waste storage show disagreement about what risk is, how it is framed and how it should be managed. Slovic argues for a view where the rules of the “risk game” is defined by affected parties. There are no universal rules, apart from relevant risk attributes such as probability and human or material consequences. Other attributes such as voluntariness, equity could just as well be included (Slovic 2001). It is true that tunnels are hard physically and contain hard technical systems. However, they exist in a social reality and a complex society. During the design process many social and soft issues needs to be incorporated but that can create conflicts with technical fire safety objectives. Therefore, a new design framework needs to be developed in order to balance these different types of issues.

2.1 Risk analysis and safety design

Often a distinction is made between hazard and risk. A hazard is a source of potential harm (ISO 2009). Uncertainty is, according to Aven (2009), central to the concept of risk. On the same line, ISO (2009) define risk as the: “effect of uncertainty on objectives”.

Risk analysis is a common method for dealing with safety within risk management in particular, and engineering in general. Risk analysis can treat uncertainty in different ways. Paté-Cornell (1996) introduce six different levels (from 0 to 5) of how uncertainty is treated. At level 0, the first step in risk analysis, *risk identification*, is carried out. This can be sufficient for a strict zero-risk policy or for low cost decisions when the options are clear. Analysis at levels 1 and 2 consider a *worst* or *plausible worst* case and can be an option if this is enough to support a decision, e.g. to design for the maximum credible earthquake. The likelihood of occurrence is only implicitly considered. Analysis on Level 3 uses the best estimate or central value that reflects the most probable outcome and may be used in Cost-

Benefit Analysis (CBA). An analysis on level 3 has a poor capability to capture the uncertainty of the outcome (Paté-Cornell 1996). At levels 4 and 5, a Probabilistic Risk Assessment, or a Quantitative Risk Analysis (QRA) is performed. A set or continuum of scenarios with associated probabilities is used in contrast to Level 1, 2, or 3 where only one scenario was selected. This includes the worst case, plausible worst case, central values and a set or continuum of other scenarios. The output of level 4 is a risk curve over the likelihood for different consequences. This curve represents the uncertainty involved under the limitations of the method used and the assumptions made. At level 5 competing models and assumptions are taken into consideration and results in a distribution of risk curves providing an estimate of the inherent uncertainty of the risk measures (Paté-Cornell 1996). The success of risk analysis at various levels is dependent on resources, available knowledge, models and data. In some cases, it is not advisable to perform an analysis at level 4 or 5 because there may not be any numerical models or data available. Note that uncertainty also can be analysed through a parametric sensitivity study and expressed in words by stating the knowledge and knowledge-gaps, outside the scope of Level 0 – 5 above.

The ethical thought patterns that most often are used to justify safety decisions can be related to deontology and utilitarianism (Hansson 2007a, Basta 2014). Within deontological ethics the core idea is that there are certain rules or duties which must not be violated, regardless of the consequences of adhering to these rules or duties. At least these consequences play a subordinate role. According to Kant (1724-1804) one should act according to personal rules, which could be accepted as common rules, valid for all people regardless of circumstances. Another version claims that we should treat other persons as goals in themselves and not only as means to some other good. Thus, within limit-based design, safety decisions are justified with reference to safety limits, on the same basis as the ethical theory. For example deontology judges an action as either right or wrong (Hansson 2007a, Basta 2014). An example could be the specification of a design fire that a given ventilation system should handle. A critical issue in limit-based design is the selection of limits or a reference scenario since other objectives are only implicitly considered. The limit-based design approach ignores questions such as how large sacrifice, e.g. cost of protection, that is implied by the conservative limits or incredible scenario (Paté-Cornell 1996). Deontological limits are often prescribed in regulations or design guides, e.g. the minimum distance between exits, but they can also be derived in performance-based design. Deontological safety levels are, perhaps correctly, accused of being magic numbers (Ingason 2008a). A strict limit-based design approach may ultimately lead to the banning of all risky activities. In this sense limit-based design may infringe on the same values set out to be achieved, which may cause more risks than it could possibly prevent (Basta 2014). An example relevant for road tunnels is road deckings that, due to very conservative explosion scenarios involving dangerous goods (FAVEO 2010), sometimes cannot be realised. Then society loses the city planning advantages of the road decking, i.e. social risks may increase, while the overall risk of dangerous goods transportation is unchanged. Obviously, safety is not the only value or goal that humans strive for (Elvebakk 2005). Although limit-based design appears to be at odds with the basic rationale of decision-making, it is common in fire safety, e.g. the use of design fire, or quantitative design criteria for fire safety objectives in performance-based design.

Utilitarianism is about specifying the advantages and disadvantages of each alternative and choosing the alternative with the greatest net advantage. Another way to phrase this is to maximise the utility. There are different ways to interpret utility or advantages, where the most common are in terms of happiness, well-being or preference-satisfaction (Brülde 1998). The utility-based design approach to safety rests on utilitarianism and argues that enough safety is achieved if the utility is maximised (Basta 2014). Most decision theories are based on the idea that the choice depends on the probabilities of various consequences and their utility, or value, to the decision-maker (Meacham 2004). The logic is to choose the option that obtain most of what you want. In the fire safety context, utilities are for example property, cost and life. The CBA framework is most often used for utilitarian evaluations (Meacham 2004). In the CBA-based design approach, the question ‘How safe is safe enough?’ is translated into the cost factors that are included in the analysis. CBA weigh advantages and disadvantages collectively, ignoring who loses or gains. From a moral perspective an unjust societal arrangement could produce more utility as measured by the CBA than a just one. Therefore, other relevant factors, e.g. justice and fairness, need to be acknowledged in the recommendation in addition to identified costs and benefits. Minorities with special needs, e.g. disabilities, are not visible in statistical estimates and are therefore ‘sacrificed’ for the needs of the majority (Hansson 2007b, Ersdal and Aven 2008). Another controversial issue is how costs and benefits are to be compared over time. Economists have developed a widely accepted solution to this problem by discounting the future. According to Fischhoff and Kadvany (2011) it is questionable how well this applies to public decisions, e.g. future generations may not benefit from money that is saved today at the cost of the environment, and there is no obvious justification for discounting future lives. Another ethical issue is the relation between the three risk parties: decision-maker, beneficiary and risk-exposed, e.g. textile factory workers exposed to poor fire safety and working conditions with beneficiaries abroad (Hermansson and Hansson 2007). These are examples of factors that are excluded or poorly treated in both a limit-based and CBA-based safety approach (called “Other factors” in Table 1).

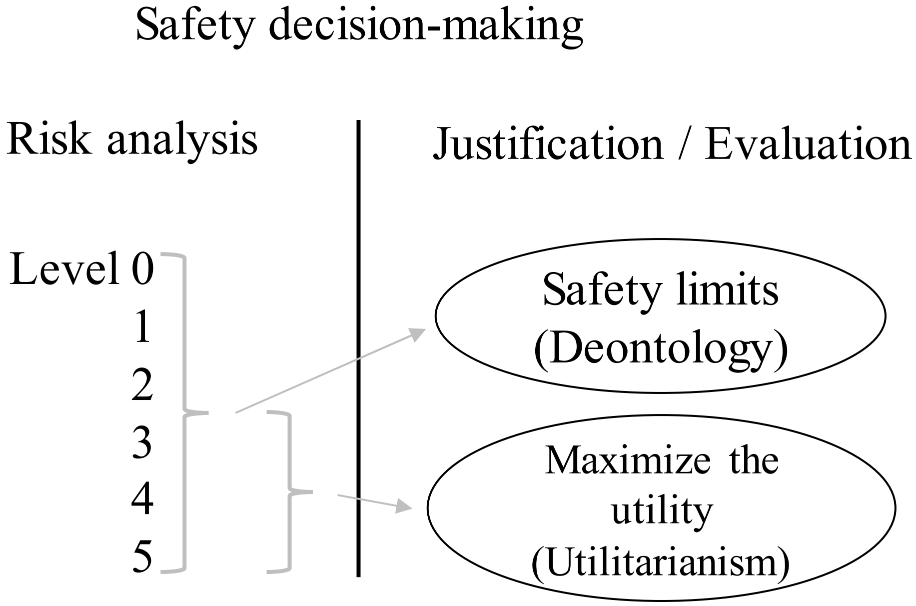

Figure 1 Risk analysis (left side of figure) can treat uncertainty to different degrees (as defined by Paté-Cornell) and decisions can be justified (right side) with regards to safety limits or maximization of utility.

To summarize, risk analysis treats uncertainty to different degrees (i.e. Paté-Cornell Level 0-5 above) and an evaluation may be made on different bases (e.g. deontology or utilitarianism), see Figure 1. A design approach based on scenario identification, worst, or worst plausible case (Level 0, 1 or 2) is a limit-based design approach limited to issues of fire safety where risk is not traded with other objectives. A design approach using the most probable outcome (level 3) in a CBA is a utilitarian design approach where risk is traded with cost. In risk analysis at level 4 or 5, risk is analysed in terms of likelihood and consequences of several scenarios. This allows for a more robust CBA in a utilitarian design approach, but could also be compared with a risk limit, i.e. a deontological criterion which could be more or less conservative and costly. These two design approaches may also be combined, e.g. in the As Low As Reasonable Practicable (ALARP) concept where the risk curve (Level 4 or 5) is required to be below a tolerability level (deontological limit) and CBA (utilitarian) is used to ensure that reasonable and practicable safety measures are implemented for the residual risks below this level but above a lower level judged as acceptable (HSE 2001, Bouder et al. 2007).

2.2 Fire Safety Engineering

The discipline of fire protection engineering (FPE) emerged in the early 20th century as a distinct discipline, in response to new fire problems posed by the industrial revolution and promoted by the insurance industry. Initially FPE focused on protection of large factories (mainly to save property) and prevention of sweeping conflagration fires in cities. As the buildings grew taller life safety was compromised at the higher levels (Grant 1993). In 1911 a fire in a tall building killed 146 garment workers in New York City. In response the US National Fire Protection Association (NFPA) Technical Committee on Safety to Life was created which ultimately lead to NFPA 101, the Life Safety Code (Perkins 1913). In an early report on UK factory fire safety, two parts of fire safety were recognised: fire prevention and fire protection. Fire prevention, argued to be the more important of the two, concerns the minimization of all means by which a fire can start, prevent the fire from spreading, and provide adequate means of escape. Protection on the other hand was provided by first-aid fire appliances to extinguish small fires and a fire brigade to extinguish larger fires (Thorpe 1919). In 1995, several of the most prominent professors of the fire science field made a common effort to produce a knowledge framework for FSE. The working group stated that the core of a FSE degree program consisted of the following five modules (Magnusson et al. 1995): fire fundamentals, enclosure fire dynamics, active fire protection, passive fire protection, human behaviour and fire. Three key steps of FSE are to identify and characterize the fire hazard, to evaluate appropriate fire protection strategies, and to find cost-effective solutions (Magnusson et al. 1995). Today most FSE work as consultants for the industry, government, insurance companies or in fire and rescue services. There is also a strong coupling between FSE and regulation. Historically, largely prescriptive requirements based on historical fire accident investigations have been the dominant approach to building safety.

As the field of FSE has evolved, regulation has allowed a performance-based option to prescriptive provisions, allowing the fire safety design to be engineered by fire safety engineers. In this work FSE draws much upon risk management (Magnusson et al. 1995). The risk management process, as defined by (IEC/ISO 2010), is laid out in Figure 2.

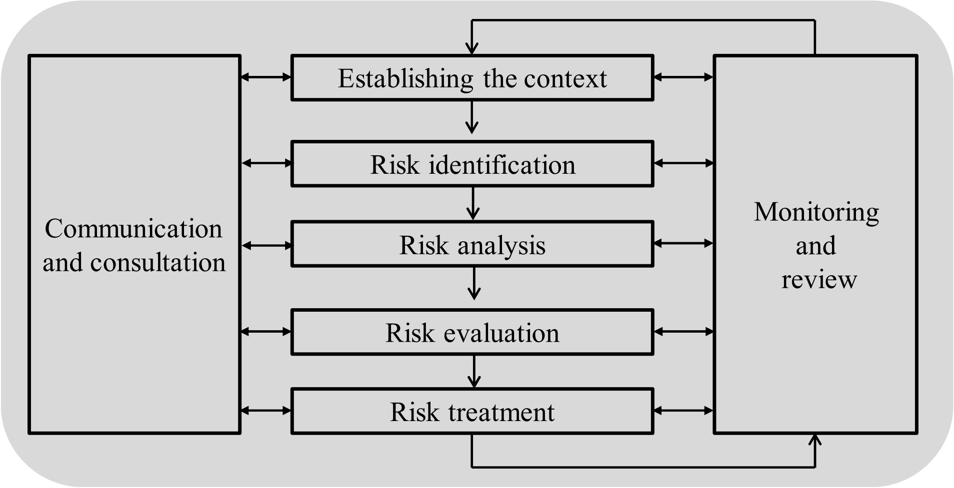

Figure 2 A view of key stages of the risk management process (IEC/ISO 2010).

Performance-based fire safety design is the focus of this thesis. In the SFPE Engineering guide to Performance-based fire protection, a process is laid out. The process starts with definition of project scope, identification of goals, and definition of stakeholder and design objectives, followed by development of performance criteria. then fire safety objectives are transformed into measurable criteria (SFPE 2007). In the SFPE performance-based design process, fire safety objectives are verified for a set of design fire scenarios. The key FSE objective is often that all occupants should be able to escape without experiencing or developing serious health effects. The FSE approach for showing that this objective is met is that the available safe escape time (ASET) is larger than the required safe escape time (RSET) by a margin of safety (Meacham and Custer 1995). Trial designs are developed and evaluated against the performance criteria. If the performance criteria are met, the design may be selected and documented. Although cost or other objectives could be considered when performance criteria are developed, the process does not include any weighing of safety against other objectives, i.e. it is in theory a limit-based design approach.

Lundin (2005) investigated several FSE projects in Sweden and identified some fundamental problems concerning society's ability to control fire safety by performance-based building regulations, which leads to arbitrary design decisions. Bjelland and Njå (2012) found that current practice of ASET/RSET analyses in the Norwegian building industry are used to confirm that chosen solutions are sufficient while the analyses themselves have limited constructive value for engineering design. Out of 75 examined projects, none contained evaluations of more than one design alternative (Bjelland and Njå 2012). According to Babrauskas et al. (2010), the ASET/RSET concept is limited precisely because it is used, as the examples just cited illustrate, to verify fire safety to an "acceptable level", rather than to find the best solution to the fire safety problem. FSE projects commonly ignore the wide potential variation in fire scenarios, human capability and behaviour in fire. According to Babrauskas et al. (2010), roughly half of all deaths and 2/3 of the injuries from home fires could be prevented if more time was available for escape. Other methods, e.g. the concept of inherent safety or fail-safe design, may provide other types of solutions that are more robust and less dependent on the assumed human capability and behaviour in fire. Generally, there is no legislative or regulatory objective to maximize fire safety. In a typical performance-based building project, many alternatives will often be worked through in a qualitative design sense, e.g. natural versus mechanical ventilation for smoke control. Many different attributes can be considered, including fire safety, before a tentative design decision is taken, which must then be checked for acceptance by modelling and analysis. Although FSE and performance-based regulation have undergone large changes and improvements, it is still an open question whether the fire safety problem is being controlled in a performance-based regime. Later studies confirm an inconsistency in the level of performance achieved (Alvarez et al. 2013). Alvarez et al. (2014) propose a paradigm shift from one in which fire is the centre of the problem to one in which building objectives are evaluated in case of fire events. Numerous challenges for performance-based fire safety design are identified by Alvarez et al. (2013, 2014), including e.g.:

- performance criteria should be determined by policy and decision makers, not fire safety engineers,
- too much focus on consequences of design fire scenarios on narrow aspects of building performance,
- the fire safety design process and the selection of design fire scenarios should not be an isolated process from the overall performance, and
- lack of appropriate or comprehensive basis for comparative analysis with a reference design.

Meacham (2004) argues that fire safety design, involving modelling of fire and human behaviour with significant uncertainties, has reached the realm of post-normal science. Post-normal science was coined by Funtowicz and Ravetz (1992).

They argue that the limit of science is being reached for risk analysis involving ineradicable uncertainties in value-laden contexts. Awareness of complexities in both the factual and the value-laden dimensions of the problems are necessary, which they call post-normal science. The gap between scientific expertise and a concerned public can be bridged by dialogue among all stakeholders. The democratization of the political life of modern societies means ordinary people can read, write, vote and debate. Funtowicz and Ravetz (1992) hope that a similar democratization of knowledge in society will take place, creating space for enhanced participation in decision-making for common problems, which is necessary for meeting the challenges of modern times. This requires that the problem is framed in a way that acknowledges the different perspectives of the stakeholders, e.g. trustworthiness of managing institutions (Funtowicz and Ravetz 1992; Wynne 1992).

Bjelland (2013) studied several FSE projects and argues that FSE becomes an activity of structuring goals and performance criteria into mathematical language. This approach assumes well-structured problems and leads to a narrow view on what is considered as relevant knowledge (Bjelland 2013). In line with post-normal science and in response to case studies of fire safety engineering projects, Bjelland (2013) propose to add constructivism and design science to the fire safety design framework. Design science can be seen as a reflective conversation with the situation that highlights the skills and experience that designers and engineers bring to situations of uncertainty and value conflicts. Important designer skills include creativity and the ability to frame the design problems in different ways. Design processes are not linear, and the stakeholders' goals and values will be conceptualized and refined during the cyclic design process. With a constructivist perspective risks are social constructs and risk evaluation can be described as a never-ending learning that starts by expressing the situation where the perceived problem lies, while not distorting the problem into a preconceived or standard form.

2.3 Towards a decision-oriented framing

According to Fischhoff and Kadvany "the foundations of risk lie in decision theory, which articulates concepts whose emergence must have begun with the first human thought about uncertain choices" (Fischhoff and Kadvany 2011, p. 2). The logic of decision-making is to choose the option that promises most of what you want. Meacham (2004) has written a review on decision-making for fire risk problems. Most decision theories are based on Bernoulli's concept that choice depends on the likelihood of various outcomes and on the utility of those outcomes to the decision-maker, e.g. Expected Utility Theory. Social Choice Theory is a concept of rationality for synthesizing preferences among individuals affected by the decision, e.g. consensus building that considers primarily the facts and values of those participating in the development of fire safety regulation. Once a regulation is in place, CBA plays a more central role when fire risk decisions are required for specific projects (Johansson 2001). In this case the decision-maker is less concerned with the "social good" than providing an "acceptable" level of safety at a minimum cost (Meacham 2004). For tunnels the situation is different. The Swedish Transport Agency (Transportstyrelsen) is responsible for tunnel regulations and ensuring that authorities, companies, organisations and citizens abide by them. The Swedish Transport Administration (Trafikverket) and larger cities plan, design, build and operate road tunnels. In any case the social good should have a high priority. It should be relatively straight forward to weigh benefits against costs for road tunnels (Boverket 2005b).

Decision-making is fundamental to all fields, not least to engineering and design work. A general model called PrOACT which is applicable to any decision is offered by Hammond et al. (1999). The method consists of eight elements: problem, objectives, alternatives, consequences, trade-offs, uncertainty, risk tolerance, and linked decision. According to Hammond et al., the essence of the method is to divide and conquer. By systematically breaking down the problem into smaller parts focus can be directed to the most critical aspects. To focus on the most important parts the process should rather be cyclic, i.e. iterative, than sequential. We should acknowledge that fire safety design fundamentally is a decision-problem. Naturally there is a difference between decision-making in theory and decision-making in reality. Real conditions are dynamic and continually changing, goals are ill-defined, and tasks are often ill-structured. However, if fast decisions such as the ones that face fire fighters during fires are omitted, similar sequences to PrOACT is often followed although it may be limited to one alternative for each iteration and about satisfying rather than optimizing. In other words, find one alternative that satisfies your goals, rather than the best solution (Klein et al. 1993), which, in line with the examples above seems to be how fire safety engineers are working in practice (Babrauskas et al. 2010, Bjelland 2013).

Compared to Figure 1 at the onset of the previous section, where analysis is restricted to what is emphasized in risk analysis or CBA, more stages in the design and decision-making process are emphasised (namely problem framing, decision objectives and generation of alternatives). From an ethical perspective, to the ethical theories' deontology and utilitarianism, a third ethical thought pattern may be added; that of a social contract. This highlight several basic mechanisms of democratic societies such as that of consent, social benefits and the idea of a society that works to our advantage. To this, Habermas discourse ethics may be added which highlight a participatory perspective rather than an observer perspective (Hansson 2009). For risk and safety, this highlight the activities of risk communication, dialogue and consensus meetings along the decision-making process to include the exposed and their perspectives (Hansson 2013).

Along the decision-making process, analysis is adapted to the objectives, e.g. life safety with risk analysis, fairness is analysed with ethical analysis (Hansson 2018), and CBA on the objectives that can be expressed in monetary units. Justification or evaluation is done by identifying the alternative with the highest utility on all objectives together. Here the tools from decision theory can be used to successively dismiss inferior alternatives and obsolete objectives (objectives for which all alternatives have the same score). In a simplified way, this is visualized in Table 1 for the three design approaches limit-based design, CBA-based design and decision-making in general.

Table 1 Limit-based design, CBA-based design and decision-making in general considers more or less factors to be relevant in a fire safety decision.

Objective	Limit-based design	CBA-based design	General decision-making
Fire Safety	**X**	**X**	**X**
Cost		**X**	**X**
Other factors			**X**

If safety is seen as a decision problem, one could aim for an optimal solution. Utility theory can act as a logical framework for rational choices among given alternatives. To know that an optimal solution is found, all alternatives need to have been explored. In practice the range of alternatives may be infinite and resources limited which means that we often must make do with an alternative after a moderate search (Simon 1996). Whatever our ambitions, it becomes important to discuss what goal or aim we have. At first glance it may seem that Vision Zero on the road network is little less than an unrealistic goal. However, Vision Zero is much more than the distant goal of zero deaths or serious injuries on roads. Vision Zero is a design philosophy that calls for necessary innovations so that no people are killed or seriously injured on the road network. Zero is not a target to be achieved by a certain date, it highlights the optimum state of the road system (Tingvall and Haworth 1999). Vision Zero assumes error and mistakes will continue to occur. Under such conditions, it is the responsibility of the system designers to ensure that the road system (roads, vehicles and users) is inherently safe, i.e. eliminate errors, or at least implement fail-safes, i.e. systems that are forgiving of errors such that the exerted violence on the human body is tolerable (Tingvall 1997, Tingvall and Haworth 1999, Tingvall et al. 2000). Inherent safety followed by fail-safe design are identified as the two most efficient safety concepts within safety engineering by

Möller and Hansson (2008). In the Vision Zero design philosophy, safety should be an inherent property and engineered into the system from the start rather than reactive measures taken to correct inferior solutions. Incremental fixes or safety systems added to imperfect solutions is not good enough. This sets higher or at least different requirements than what is typically analysed and engineered in limit-based or utility-based design. Rather than an *acceptable* or a *safe enough* solution, the aim is to achieve a close to *absolutely safe* system that is forgiving to human errors and mistakes with the exclusion of extraordinary events e.g. violations) (Tingvall 1997).

Compared to traditional safety approaches, Vision Zero can create innovations and improved solutions (Whitelegg and Haq 2006). Despite this potential, Vision Zero has been criticized for not being successful. Andersson and Pettersson (2008) argue that the strong visionary and idealistic political goals in Vision Zero supress critical objections and can create lock-in effects and actually prevent effective policies from being implemented. Elvik (1999) estimates that the cost of reaching Vision Zero would be many more lives lost in other areas of society. A strict focus on reaching Vision Zero can therefore be unethical since it implies that other values, including safety in other areas, are disregarded without any justification (Elvebakk 2005, Bany 2013). Elvik (1999) argues for a more pragmatic and utilitarian interpretation of Vision Zero. If we are ever to realise the goal, Vision Zero calls for an efficient use of resources, which means resources should be allocated to the lowest net cost to save lives. However, this contradicts the principles and ideas behind Vision Zero, where economy is regarded as a means towards safety. Only if two measures offer the same level of safety can CBA be used to choose between them (Tingvall 1997). A strict focus on utility-based design may create lock-in effects towards current solutions and technology since they often will be the cheapest option. Limit-based design is even more probable for creating lock-in effects towards inferior solutions, since it is sufficient to find one acceptable design that fulfils the pre-defined criteria (Babrauskas et al. 2010, Bjelland and Njå 2012). Although cost is downplayed in Vision Zero, inherently safer or fail-safe solutions are not necessarily more costly than other solutions. Indeed, in the long run they may very well pay off (Rosmuller and Beroggi 2004, Whitelegg and Haq 2006). Given that society wants improved safety, Vision Zero emerges as the best starting point. Other aims such as cost can be included in the decision process in support of the identified overarching vision. The next subsection is devoted to theory about tunnel fires.

2.4 Tunnel fire dynamics and modelling

In tunnel fires fresh air is usually transported to the fuel with the ventilation flow which sustains the fire. In tunnel fires the hot smoke initially rise and impinges on the ceiling, extends along the ceiling and gradually descends towards the floor as it is being cooled, see Figure 3. The amount of back-layering and the distance downstream that the smoke remains stratified is highly dependent on the ventilation conditions (Ingason 2012, Ingason et al. 2015).

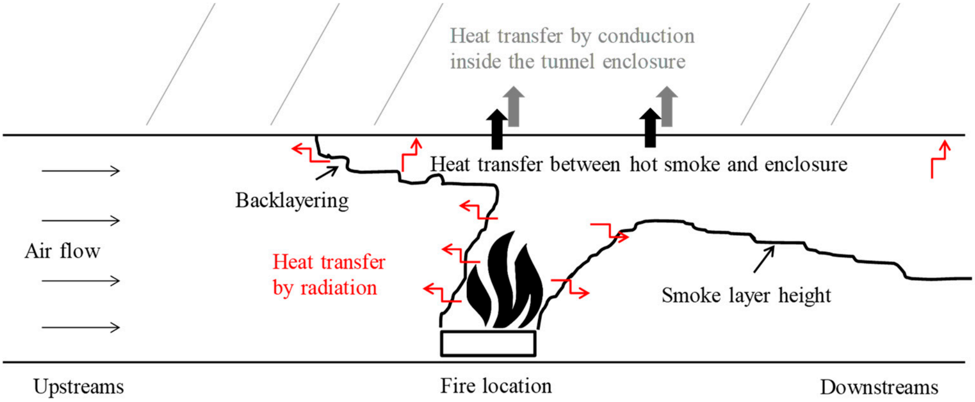

Figure 3 A fire in a tunnel with longitudinal ventilation flow. The smoke follows the flow apart from some backlayering to the left. Initially the smoke is stratified along the ceiling. With time and increasing ventilation flow the smoke is mixed with cold air and reaches the floor level. Heat is transferred by conduction and radiation.

In recent years, a comprehensive theory on tunnel fire dynamics has started to develop. Fire parameters such as the gas temperature development, flame length, back-layering, visibility in smoke and gas concentrations can be calculated for tunnels with longitudinal air flow (Beard and Carvel 2012, Ingason et al. 2015). The first tunnel fire science study was performed by Thomas (1958) to study the effect of back-layering, when hot smoke travels upstream along the ceiling against the air flow, see Figure 3. Later Thomas (1968) introduced the concept of a critical air velocity needed to prevent back-layering. The critical air velocity, which is the most studied parameter in tunnel fire dynamics, will increase with the heat release rate (HRR) towards a constant value at around 3 m/s for most tunnels (Ingason 2008b, Ingason 2012). It is, however, not obvious what makes this air velocity *critical*, there is no evidence found in the literature that back-layering has ever impaired fire safety. Secondly, in bidirectional road tunnels the so-called *critical* air velocity, compared with a minimal ventilation, might worsen safety since the fire develops faster in the presence of ample ventilation and smoke is pushed towards evacuees downstream the fire.

Engineering often relies on quantitative modelling of phenomena. Modelling of fire in general, with tunnel fires being no exception, is challenging as several basic mechanisms, e.g. pyrolysis, combustion and fire spread, are very difficult to model. Furthermore, modelling assumptions are numerous, e.g. the grid size, radiation model, turbulence model. In single comparisons between computer simulations and experimental data good results are often reported, e.g. (Hadjisophocleous and Jia 2009). However, a round-robin study involving 11 independent teams reveals another picture (Rein et al. 2009). A significant spread in the simulated results was found, even though each team received the same information of the basic fire test set-up that was to be modelled. Due to several stochastic variables and limited knowledge, the modelling of fire and human behaviour for tunnels will be highly uncertain (Beard and Cope 2007, Ferkl and Dix 2011). The conditions for reliable and acceptable use of complex computer models for tunnel fires do not yet exist, models may only be valuable in a qualitative sense rather than quantitative (Beard 2012a). This highlights the potential for using tunnel fire dynamics theory as a compliment to complex computer models to analyse tunnel safety and risk.

2.5 Theoretical framework

In the philosophy of science, a theory is a series of statements that together describes a segment of a phenomenon. It is congruent with a specific research tradition (paradigm). Theory will always be incomplete; it can never describe a phenomenon from all perspectives. Therefore, theoretical frameworks require positioning. For the purpose of this thesis, a theoretical framework will be defined as ‘a structure organized around a theoretical perspective that is applied to solving a specific research problem’. I believe knowledge implies social responsibility for the well-being of fellow beings. I therefore agree with the way Fuller (2004) argues that we should see ourselves as intellectuals, implying that we have an individual responsibility for our own research approaches and products. It is not enough to simply internalize how researchers in my field conduct their research; I must actively take a stand. This is a learning process; along the way, the paradigm of the field, its limitations, and rival theories are being discovered.

Two contrasting views on science are offered by Thomas Kuhn and Karl Popper (Fuller 2004). Kuhn described science as it was: each field with its own culture and paradigm of what knowledge is, what theories that are ‘true’ and which methods can be used to generate knowledge. The research paradigm must be internalized if anyone is to be accepted into the field. Kuhn called the ordinary work carried out by scientists for “puzzle solving”. In this sense, existing experiments are replicated, and accepted methods are applied to gradually generate new knowledge. Paper II and III share typical traits of puzzle solving work. Paper II is based on traditional empiricism where a model is compared with quantitative experimental data. Paper III uses accepted methods and structures from fire safety engineering on road tunnels. In contrast, Popper dreamed of a science that formulated brave hypotheses and tried to falsify rather than verify them. Regarding scientific discovery Popper claimed that there was no method or logic of discovery. According to Popper the so-called scientific method consists of criticism (Nola and Sankey 2007). Paper I & IV is closer to this type of critical science. Paper IV is based on criticism of fire safety design and proposes an alternative fire safety design framework. Paper IV would not have been possible without first internalising the research paradigm of fire safety design in Papers I, II & III.

2.5.1 My research problem and epistemological position

Epistemology is the theory of knowledge focused on questions such as how we can know that we know something and why. In general, we cannot know that we know much at all with certainty, as the ancient Greek philosopher Agrippa pointed out, we have to choose between the following unpalatable alternatives (Pritchard 2010):

1. Our beliefs are unsupported, or
2. Our beliefs are supported by an infinite chain of justification, or
3. Our beliefs are supported by a circular chain of justification.

This shows the importance of stating the theoretical framework and epistemological basis behind the research. Two key concepts for my research problem are safety and risk. Safety and risk are typically interdisciplinary fields which involve both engineering and other sciences, e.g. social science studies. From an epistemological perspective, risks are connected to 1) limited knowledge for describing phenomena and 2) lack of knowledge about the future. The second point is particularly problematic. Since there is much we do not know and there are an infinite number of possible scenarios, knowledge about risk relates to finding a balance between irrelevant and relevant risks (Hansson 2012).

My research also relates to the main field of my department, which is fire technology since it is the phenomenon of fire and the resulting consequences that we want to be protected from. The physical development of fires in tunnels is traditionally based on empirical investigations and reductionism aimed at discovering universal objective laws for a system by decomposing it into subsystems where scientific knowledge is available. Quantitative data, e.g. heat release rate, soot yield and toxic gas yield, from full-scale tests and laboratory studies are the main source for such knowledge. Paper III is based on experimental data and belong to this natural science tradition based on reductionism, repeatability, and refutation. A more detailed history of fire science and its theoretical framework is presented in Paper I and IV. Paper II & IV are about developing a design framework. In this thesis a design framework consists of a theoretical framework and methods, see Figure 4.

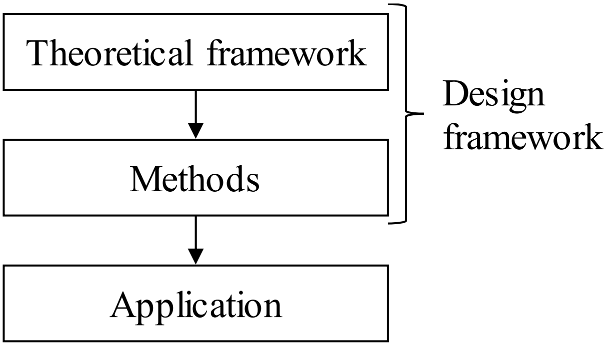

Figure 4 A design framework comprises a theoretical framework and methods that are applied to solve design problems.

A theoretical framework is on a higher level than methods and is not directly applicable to real problems. The theoretical framework offers the theoretical basis for methods that are next applied to real problems. The theoretical framework points to certain sets of methods that consider what the theoretical framework highlights to be important. In a way the theoretical framework defines the purpose and criteria that methods should achieve. In Paper II the current theoretical framework was used as a basis to adapt methods, e.g. scenario analysis, to road tunnel fire safety design. In Paper IV a new design framework comprising both the theoretical framework and methods is proposed. The scope of Paper I is a literature review comprising both theoretical frameworks, methods and their application to safety problems. Paper III is mainly concerned with the application of existing tunnel fire dynamics theory (methods) to tunnel fire safety problems, see *Figure 5* where the scope of Paper I-IV are visualized.

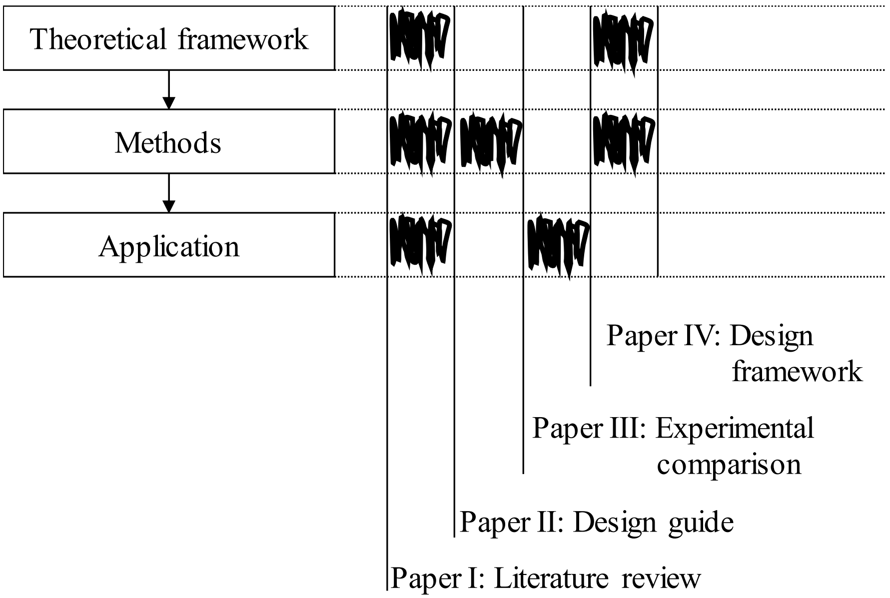

Figure 5 Paper I-IV focus on different aspects of design problems.

To Simon (1996) the design of real artefacts, e.g. tunnels, or artificial constructs, e.g. methods, are design problems, concerned with how things ought to be. In this sense the development of a fire safety design framework is a design problem. On design problems the scientific method based on reductionism, repeatability and refutation fall short. Checkland (1999) illustrates why in his conclusions that a successful application of a method to a design problem could just as well have been obtained by an *ad hoc* method. Similarly, an unsuccessful application could be caused by incompetence in application. Design problem settings cannot be created in the laboratory and two identical settings cannot be constructed. The sum of the parts of real social systems does not reveal all aspects of the whole system. In other words, the natural scientific method characterized by reductionism, repeatability and refutation does not work on design problems (Simon 1996, Checkland 1999). Instead, design methods need to be applied many times in different situations by different people. Successful application is captured by a more general experience of how well design problems are being solved. In Paper IV a design framework for fire safety design is proposed.

2.5.2 The theoretical framework in Paper IV

Normally engineering papers do not deal with theoretical frameworks, however, Paper IV is particular in that respect since it does deal with the theoretical framework of performance-based fire safety design. The interest is primarily the design framework for fire safety design problems in a performance-based regime. Bjelland (2013) calls the underlying theoretical framework of fire safety design *technical rationality* which is mainly influenced by empiricism and positivism. According to Bjelland, the current theoretical framework is too narrow to capture the essence of fire safety design. This leads to great simplifications and exclusion of critical issues that are difficult to quantify. According to Bjelland (2013), and most likely many regulated technical risk issues, the decision problem of societal fire safety is transformed into a mathematical exercise to show that risk is acceptable or that safety is verified. In this sense, normative questions such as ’how safe should it be?’ are turned into scientific ones (Shrader-Frechette 1991). This usually means that science and engineering are not supporting decisions they are practically making decisions. Normative questions such as what action to take should not be decided by science alone. Bjelland, argues that the theoretical framework of fire safety design should be strengthened with constructivism. The dual nature of risk as a potential for physical damage and as a social construction demands a dual strategy for risk management. Public values and social concerns can identify the topics for risk management. Technical expertise can assess the magnitude and likelihood of risks, but public input is needed to set priorities and objectives (Renn 1998).

Hermansson (2005) argues that the focus in risk management should shift from the outcome to the procedure for decision-making. Those affected by a risk decision should have the opportunity to be involved in a fair decision-making process. Public participation is a goal for democracy and a requirement for rational decision-making (Renn 1998, Hermansson 2010).

Knowledge relevant for justifying decisions is moral knowledge, which also is problematic from an epistemological perspective since it may seem subjective at a first glance (Pritchard 2010), although most knowledge has subjective elements. Roeser (2006) even argues that emotions are an indispensable normative guide to the moral acceptability of risks. Emotions may be subjective, but they highlight our preferences. Moral knowledge can be obtained and is, according to Roeser (2006) necessary for making rational risk decision. This emphasizes ethical aspects, e.g. fairness, in risk decisions. As was described earlier, the decision-making process in performance-based fire safety design is informal and not very transparent; many important decisions are made before a solution is verified using the formal procedure for performance-based FSE. I argue for that the decision-process should be emphasised and treated more formally in fire safety design.

Beard (2012a) propose an intermediate methodology for tunnel fire safety decision-making between *hard* and *soft systems* methodologies. By a *hard* methodology Beard argues that there is an agreement as to what the problem is, and it can be mechanically solved without any iteration and low uncertainty from problem to solution. At the other end of the spectrum, *soft systems* methodology features different opinions as to what the problem actually is and how it reliably could be solved. The problem solving process is seen as a learning process and the problem is solved when the problem owner feels it to be so (Checkland 1999). Tunnels are hard physical and technical systems. Tunnels also exist in a social reality and a complex society, and during the design process many social and soft issues surface that can conflict with technical fire safety objectives. An example could be a ventilation shaft that intrudes into the habitat of an endangered species, or arguments that safety resources are better used elsewhere.

Shrader-Freschette (1991) argues that rational risk evaluation takes a middle way between cultural relativists and naive positivists. Both the cultural relativist and the naive positivist err in being reductionist. The cultural relativists try to reduce risk to a sociological construct, underestimating or dismissing the scientific component of risk; while the naive positivist try to reduce risk to a purely scientific reality, underestimating or dismissing the ethical or democratic component. Shrader-Freschette argues that rational risk evaluation acknowledges both the scientific and ethical/democratic component of risk.

In line with Bjelland, Renn, Hermansson, Beard and Shrader-Freschette, the theoretical framework that Paper IV proposes is found between the *hard* and the *soft system,* or between positivism and cultural relativism/constructivism, arguing that both sides highlight important aspects of risk, but neither can claim universal validity. A fair and democratic process matters for sound risk evaluation together with technical and quantitative factors.

3 Method

A method is a way of working consciously under certain conditions, according to a plan. There are methods for anything, e.g. cooking or gardening, it would indeed be surprising if one would not find methods also in science: methods as practices (e.g. laboratory work), systematic arrangement of topics, discourses or ideas (e.g. a literature study in Paper I), methods as heuristics in theory construction (e.g. the structure of performance-based requirements in Paper II), methods of discovery and justification (e.g. comparison with empirical data in Paper III), and methods to solve design problems (e.g. proposed design framework in Paper IV).

From a social perspective the scientific method can be seen as professionalization of the scientific quest for well-founded beliefs. This can be exemplified by values or virtues that a scientist or theory should have, e.g. precision, accuracy, testability, consistency, usability, generality and simplicity, or the will to understand and explain in order so see the bare reality itself (Nola and Sankey 2007). Indeed, I have found inspiration in the work of great scholars such as Sven-Ove Hansson, Claudia Basta, Katherine Shrader-Frechette, Baruch Fischhoff, Eric Hollnagel and James Reason. Another inspiration has been found in the many courses I have had the opportunity to study across Sweden, e.g. Risk Philosophy at KTH Royal Institute of Technology, Research Ethics and Philosophy of Science at University of Borås, Tunnel Fire Dynamics at Mälardalen University and Human Factors and Risk Management at Lund University. The methods that have been applied in Papers I-IV are presented below.

3.1 Literature studies

Systematic studies of road tunnel fire safety and risk literature have been conducted during the whole process with the aim to learn what has been presented previously and to progress on the research objectives. The main sources for information were books provided by the library of RISE Research Institutes of Sweden and Scientific databases and journals provided by Lund University, in particular LUBsearch/EBSCOhost, which among others includes ScienceDirect and Scopus. Some of the most important literature references have been suggested by peer reviewers during the review process of the four papers. Another source for latest research and literature references has been scientific conferences such as the International Symposium on Tunnel Safety and Security (ISTSS) 2010, 2014 and 2016, the Safety and Risk Conference PSAM11 & ESREL 2012 in Helsinki, and Society for Risk Analysis (SRA) Nordic 2015 and 2016. A secondary source of information has been the Google search engine. A literature study was an essential method in Paper I, II & IV. The most frequent keywords have been: safety; risk; road tunnel; fire; risk evaluation; Vision Zero.

A literature study is a descriptive method, it aims at describing what others have done, providing an overview of the field, how certain theories, methods or concepts are applied, or how a certain goal, e.g. safety, is achieved in different settings. Few studies have been made that investigate how road tunnel fire safety is designed in practice. Therefore, interviews were conducted to bridge a potential gap between theory and practice.

3.2 Interviews

In order to gain knowledge of the fire safety design process of Swedish road tunnels, semi-structured interviews were performed with seven selected professionals. The seven professionals included in the interviews, were selected because they had extensive relevant experience and were currently involved in the design and decision-making of fire/safety/risk issues in large infrastructure tunnel projects. They were also selected to cover several different types of professional work on different projects and in different roles, e.g. fire consultant, safety officer, client support or fire safety design team. One interview lasting for about one hour with three professionals from the same consultant company was performed in 2010 to understand the use of risk analysis in underground design. Two interviews (each three hours long) were conducted in 2012, within the scope of RO1, to better understand the Swedish design process and how a performance-based design guide should look like. Finally, two one-hour long interviews were made in 2018 exploring the application of Paper IV to road tunnels. The questions in an interview may be more or less structured beforehand (Ejvegård 2003). In these interviews, open explorative questions, such as ‘How are fire safety design decisions made in practice?’, ‘How would you describe the process?’, ‘Who participate in the process?’, or ‘What is dimensioning fire safety?’ were prepared before the meetings. In this sense all interviews were semi-structured; questions were prepared, but no options were given, and questions could be changed or invented during the interview. The type of questions that were going to be used were sent to the interviewees beforehand so that they would be prepared. The interviews were recorded. Afterwards the notes and recordings were worked into a written summary. The interview material, were used in Paper II, Paper IV and Chapter 0 of this thesis, similar to how other literature was used with the difference that a reference is made to the interview material instead of a literature source.

3.3 To derive a performance-based design guide

The context for this method and the resulting work was a research project undertaken by Lund University and RISE Research Institutes of Sweden, funded by the Swedish Transport Administration. The work was carried out in a project group together with a reference group established for the project. The project group consisted of five researchers that together shared many years of experience within (tunnel) fire safety research and fire regulation. The group meet every second to every fourth week during a one-and-a-half-year period. Most meetings required preparation, i.e. reading and commenting a new piece of text. The reference group consisted of one Norwegian and 12 Swedish participants, mainly tunnel fire safety consultants and tunnel owners, i.e. the Swedish Transport Administration and City of Stockholm. The reference group meet three times and offered feedback during the work as well as on the final design guide. The aim was to derive a performance-based design guide for road tunnels. The first step consisted of a literature study. In this sense, existing laws and latest tunnel fire research and how to specify performance-based requirements within structural and fire safety engineering was internalized.

As a compliment to the literature review, the project group performed interviews with two professionals to better understand the design process today. Among the possible guideline structures identified in the literature study, the most suitable was selected. Performance-based requirements were formulated that define the functional objective that the tunnel solutions should fulfil. Assessment takes inspiration from the Swedish building regulation, (BBR26 2018, BBRAD3 2018). Prescriptive requirements must be fulfilled; however, it is the choice of the design team to either adopt the proposed acceptable solutions, or to design alternative solutions by verifying that the performance-based requirements are satisfied. Thus, acceptable solutions and a procedure for compliance were identified from legal requirements or best practice or derived from tunnel fire safety literature. Group discussions was used to evaluate advantages and disadvantages of different factors, e.g. performance-based requirements and acceptable solutions and hierarchal structures by reaching consensus or compromises. The method to derive a performance-based design guide for road tunnel fire safety is summarized below in the following steps.

1. Literature study of performance-based design and interviews with Swedish tunnel fire safety design professionals.
2. Restructuring of tunnel fire safety legal requirements, guidelines and best practice into a selected model structure.
3. Formulating performance-based requirements that define the fire safety functions that the tunnel should have.
4. Adding or calibrating acceptable solutions or functional requirements and means for compliance.
5. Iteration with the project group and reference group.

Note that the suggested level of safety reflected the view of the project group and current tunnel fire safety state of the art. It was not calibrated against other factors such as cost or fairness.

3.4 An empirical comparative method

Paper III adheres to the traditional engineering method of empiricism. First tunnel fire dynamics formulae were transformed into a model of the time to compromised tenability in tunnel fires. The time to compromised tenability was chosen since that is the key parameter of interest in tunnel risk analysis. Tenability thresholds, e.g. visibility, heat, radiation and toxicity were identified from literature. The time to compromised tenability was calculated in MS Excel. Next the tenability model was compared with measured empirical data from previously conducted tunnel fire experiments. The experimental data came from eight tests from three different experimental settings among which five were full scale fires in real tunnels and three were model scale tunnel fires. The experiments were chosen because they measured the required data under varying conditions, e.g. measurement position, fire size and ventilation, i.e. to optimize the validity of the comparison. For empirical models, data uncertainty must be considered.

The input parameters to the model were classified in three groups: #1 known input parameters that were measured in the experiments, e.g. fire size as a function of time (considered to be certain), or #2 constants that were considered to be certain, e.g. molecular weights, or #3 constants that were seen as uncertain, e.g. yields, effective heat of combustion or optical smoke density. With the use of sensitivity analysis, the uncertain input parameters to the model were varied within plausible endpoints to infer how this affected the output, i.e. this is a measure of the reliability of the formulae. Finally, the relative difference in percentage between modelled and experimental time to compromised tenability was calculated. From the comparison and sensitivity analysis it was induced how well they predict the time to compromised tenability. Note that a model never can be ′verified′ as being right or wrong as we do not know whether the data is right or wrong can never reach perfect prediction (Beard 1997). Uncertainty from experimental setup and recorded measurements were discussed and analysed in Paper III and in Chapter 4; Results.

3.5 A design framework for fire safety design

The development of a design framework has been an iterative process with the following stages:

1. Background knowledge
2. Choice of theoretical framework
3. Choice of methods
4. Evaluation (tentative application)

This process has gradually evolved together with the background knowledge. Analysis of the background knowledge results in the suggestion of a theoretical framework which in turn gives a suggestion of suitable methods. Through iteration, the framework is evaluated and adjusted using interviews and new background knowledge. The background knowledge consists of a literature review (mainly from Paper I & IV) and interviews with designers with the aim to identify and analyse:

- How the current fire safety design process works and what the challenges are.
- How risk evaluation and safety problems can be justified or on what basis such decisions can be made.
- Alternative theories, methods and concepts that can improve the fire safety design process.

An important technique throughout Paper IV has been the process of writing and reviewing (internal and external) and the philosophical method of argumentation and critical thinking (Björnsson et al. 2009). The strength of an argument depends on its truthfulness and its relevance. Critical thinking is a fundamental trait of any scientific work and is according to Popper *the* scientific method (Nola and Sankey 2007). Critical thinking concerns a critical or questioning attitude in general, an openness to rival perspectives and an acknowledgement of critical scientific work from literature.

Since the scientific method based on reductionism, repeatability, and refutation does not work on design problems, true validation requires many years of application and most likely also design framework refinements along the way guided by how well stakeholders feel fire-problems are being solved. As a countermeasure, interviews with professionals from the tunnel fire safety design process were made to better understand the context in which a new design framework would be applied.

4 Results

In this chapter the results of Paper I-IV are summarized.

4.1 A literature review of road tunnel fire safety and risk (Paper I)

In Paper I, a review concerning road tunnel fire safety and risk is presented. The first third of the paper is a review of road tunnel fire safety including tunnel fire dynamics theory, tunnel accidents, fire hazards, structural and human behaviour. The remaining two thirds present and discuss different perspectives and methods on safety and risk. The different methods and perspectives highlight different aspects of safety and risk. It is argued that a diversity of methods and perspectives can strengthen road tunnel fire safety, no single method or perspective can claim universal validity.

Tunnel fire safety is largely a low probability-high consequence risk issue. Small fires (5-20 MW) are seldom any issue for life safety or business continuity. Larger fires occur rarely, but can mean both loss of lives as well as long tunnel closure and expensive repair costs. The uncertainty in estimating probabilities and modelling of fire and consequences is considerable. Decision stakes are often high in terms of investment costs and the risk of longer tunnel closure and life safety. As is argued by Bjelland (2013), the methodological framework of FSE is too narrow for these problems to be efficiently addressed. As is argued by Meacham (2004), the limits of post-normal science are being reached, which means that a broader group of stakeholders should be included in the decision process. Furthermore, the realm of relevant knowledge should be extended to include other sciences, concepts and methods of ensuring safety.

The paper argues that the decision-making process should not be separated from design and evaluation as they are strongly dependent and iterative processes. Decision-making is fundamental to most reviewed methods; therefore, we should acknowledge that we are dealing with a decision problem. Then the tools for decision-making can be used to structure the problem, to remove constraints and biases, to identify the basic objectives and potential solutions, to evaluate solutions and to perform trade-offs. Decision theory can guide the design and decision process in negotiation with stakeholders. Key parameters for the decision can be analysed through a combination of functional requirements, societal and political values, safety engineering, safety factors and systems theory. The importance of decision-making as a design method is further deliberated in Paper IV and Chapter 0.

Considering the fire-risk of heavy goods vehicles, which is the dominating risk in road tunnel fire safety design, the review paper suggests that an efficient pro-active safety measure may be to improve the safety culture of professional drivers and truck companies. Regulation ensuring proper maintenance, training and quality management may be necessary in a global competitive economy.

4.2 Development of a performance-based design guide (Paper II)

Paper II offers the first answer to the safety quest of this thesis, i.e. verifying acceptable road tunnel fire safety using the FSE framework and performance-based design in a Swedish context. The background is that the Swedish Traffic Administration since 1995 have been writing their own technical specifications and guidelines for road tunnels in Sweden. These technical specifications or guidelines contain a mixture of prescribed solutions, safety limits and performance-based requirements. National regulation requires that risk analysis (i.e. more performance-based) is performed in order to account for several safety parameters, but clear guidance or criteria are missing. This means that several prescriptive requirements need to be complied with, which makes the purpose and the role of the risk analysis vague; risk analysis should verify several aspects but can only to a minor extent affect the solution. In this respect the regulation and guidelines are not congruent. Performance-based regulation gives more flexibility for alternative solutions as long as the function is achieved. The idea and advantage are that this should introduce innovations, save money and make constructions equally safe or safer. In 2010 SP, now RISE Research Institutes of Sweden, was awarded a research project to develop a performance-based design guide. Paper II presents the outcome of this project.

Several legal requirements and political objectives influence how a tunnel is designed and therefore also what requirements the tunnel must fulfil. The overall requirement for Swedish road infrastructure is to ensure a socio-economic efficient and sustainable provision of transport for citizens and industry throughout the country. Keywords are availability, safety, environment and health (Trafikverket 2011). On a legal level, the planning and building act (SFS 2010:900) and the planning and building ordinance (SFS 2011:338) apply to tunnels as they are construction works. In this ordinance five basic fire safety requirements for structures can be identified from the EU Construction Products Directive. For tunnels the act on safety in road tunnels (SFS 2006:418) and the ordinance on safety in road tunnels (SFS 2006:421) further specify the requirements set out in the EC directive on minimum safety requirements for tunnels (EC 2004).

Based on a literature review carried out in the project and in consultation with the reference group, it was decided to use a hierarchal structure that draws back to the so called *NKB-model* developed by the Nordic Committee on Building Requirements during the 1970s (NKB 1978). The NKB-model provides technical guidelines on how to make a performance-based design of buildings. The Inter-Jurisdictional Regulatory Collaboration Committee (IRCC) have developed this model further (IRCC 2010). Further, the project group tried to follow the structure of the Swedish building regulation (BBR26 2018, BBRAD3 2018) as strict as possible so that stakeholders in tunnel safety will recognize the concept, and thereby more easily accept and apply the concept. An overview of the design guide structure can be seen in Figure 6.

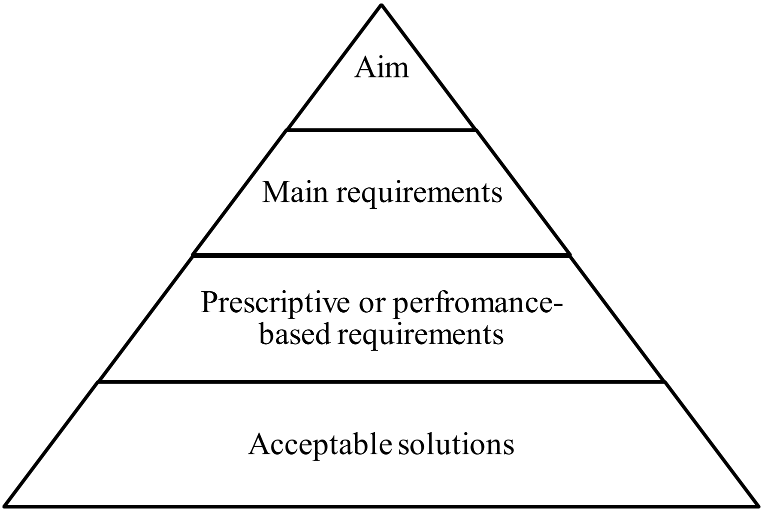

Figure 6 Overview of guideline structure. Solutions fulfil the requirements which in turn meet the overall aim.

Based on legal requirements, political goals, and latest research, requirements for tunnel fire safety are identified. In the proposed design guide, acceptable solutions (recommendations), prescriptive requirements and performance-based requirements are structured in a congruent way such that either acceptable solutions can be used, or performance-based solutions developed. To achieve this, acceptable solutions are framed in the guideline as recommendations (*may*) instead of requirements (*must).* An acceptable design can be verified in two different ways: either the recommendation, i.e. proposed acceptable solution, is followed (which is assumed to fulfil the performance-based requirement); or alternatively it is *shown* that the engineered solution fulfils the performance-based requirement. To offer most freedom to the designer, prescriptive requirements that must be fulfilled were kept at a minimum.

Taking a top-down approach a guideline was developed based on existing Swedish laws and guidelines in a hierarchal structure with four levels. At the top, the overarching aim of the guideline is stated as follows: protect life, health, property, environment, and key societal functions from fire. This aim is supported by a set of main requirements for different safety objectives, each containing prescriptive or performance-based requirements, and acceptable solutions for fire safety in tunnels. The derived design guide is appended to the project report (Gehandler et al. 2012b, Gehandler et al. 2013). In the design guide, the five main requirements (level 2 in Figure 6) which specify a fire safe road tunnel, are summarised below.

4.2.1 To limit the generation and spread of fire and smoke

This main requirement aims to offer protection against the origin, development, and spread of fire and smoke within the tunnel. It can be subdivided in four subsystems: fire compartmentation, wall-lining material, ventilation, and Fixed Fire Fighting Systems (FFFS). Performance-based design methods may be applied, or acceptable solutions may be adopted. Fire compartmentation and wall-lining material are best verified through standards, e.g. the Eurocode. This ensures that a fire will not spread or grow with the aid of the wall-lining material, and key parts of the structure such as escape routes must endure fire exposure for a certain minimal time. Fire compartmentation for tunnels primarily aims at protecting life. In the design guide, EI 60 is recommended as an acceptable level of protection considering the dynamics of a tunnel fire. Tunnel fires can be more severe than the ISO 834 standard fire curve (higher gas temperatures in the ceiling), but the dynamics of a tunnel fire follows the air flow along the tunnel which means the fire stress and the integrity of wall or doors at a height up to 3 m should not be more severely stressed than a corresponding one-hour standard fire (Ingason et al. 2015). Depending on other requirements and the overall safety concept of the tunnel, certain strategies for the ventilation system might be necessary to achieve a safe evacuation. Regarding spread and generation of fire a minimal amount of ventilation is preferable. For limiting the generation and spread of fires a FFFS can be very effective. This can also have a positive effect on other objectives such as evacuation, load-bearing capacity, and the rescue service as the fire, in general, will be smaller.

4.2.2 To provide means for evacuation

The tunnel shall offer the users the possibility to reach a place of safety in the event of an emergency. Evacuees must not be exposed to falling objects or physical obstructions, high gas temperature, high heat flux, high levels of toxic gases, or poor visibility. Assessment of compliance can either be by acceptable solutions or through performance-based design. Evacuation is a difficult area which not only depends on the fire development and technical systems, but also human factors. In tunnel fires, the toxic gases transported with the smoke is what causes fatalities. The smoke, i.e. the smoke particles, obscure the sight for the evacuee and therefore become important when considering evacuation in smoke. Life safety is therefore best achieved if evacuation through smoke can be avoided (this could be a principle defined in the safety concept). Depending on the tunnel and traffic situation this could for example be achieved in unidirectional tunnels by ensuring that the smoke travels with the traffic flow and that downstream traffic safely can continue driving. Other systems for improving the smoke conditions in the tunnel can be a FFFS or a transversal ventilation system. The need for assessment depends on the safety concept and tunnel (e.g. evacuation in smoke can theoretically be avoided for unidirectional tunnels without traffic congestion with longitudinal ventilation >2-3 m/s). For the cases when evacuation must be performed downstream in the smoke, tenable conditions for the evacuees need to be ensured. This can be achieved by complying with proposed solutions, or through performance-based design. In the guideline, performance-based design through scenario-based risk analysis is proposed. For such an analysis there are many aspects that need to be thoroughly considered, see the guideline report (Gehandler et al. 2012a, Gehandler et al. 2012b). The pre-specified scenarios set the level of safety to strive for. Note that an exponential fire growth rate was proposed in the risk assessment. This should be modified to a linear fire growth rate, consistent with the latest tunnel fire dynamics theory (Ingason et al. 2015).

4.2.3 To provide means and safety for rescue operations

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

4.2.4 To ensure load-bearing capacity of the construction

The main goal with this requirement is that the load-bearing capacity of the construction can be assumed during the event of fire. The load-bearing capacity of the construction should support a safe evacuation and rescue intervention. A collapse or partial collapse could lead to time consuming reparations or refurbishments which, from a socio-economic perspective can be costly. In the developed guideline two methods are proposed to verify that the load-bearing capacity is sufficient. The first method is based on a time-temperature curve which the design should handle for a specified amount of time. Vehicles involved in a tunnel fire are likely to burn intensively for less than one hour, however, during this time the ceiling gas temperature can be as high as 1350 °C. To use a pre-specified fire curve is a crude approach that ignores the effect from the size of the tunnel cross-section, ventilation, tunnel fire dynamics, and FFFS. Therefore, a more performance-based approach is suggested. In the performance-based approach the ceiling gas temperature is calculated from a set of representative scenarios for the load-bearing capacity. In the calculation method, parameters such as ventilation, fire size, and tunnel geometry are accounted for. This will lead to a unique time-temperature curve for the specific tunnel in question. Note that the maximum ceiling gas temperature that is proposed in the design guide depends on the tunnel enclosure material and should be lowered for rock or concrete enclosures, i.e. non-fire protected enclosures.

4.2.5 Organisation and management

As part of on-going systematic fire safety work, the tunnel manager should ensure necessary organisational, administrative and technical measures for safe operation, proper maintenance and efficient incident and traffic management. Training, learning and scenario exercises (tabletop exercises used to practise and evaluate alarm and decision chains) should be performed to validate and verify that the response to incidents, accidents and emergencies is efficient. For vulnerable tunnels, exercises and other methods should ensure that the organisation that is created before, during and after crisis is fit to take appropriate action. Verification of compliance could be internal and external administrative control, including the execution of exercises and existence of a total quality management system. To continuously improve safety during the operation of the tunnel, a quality management system is essential to structure and drive this process.

4.3 Tunnel fire dynamic models for risk analysis (Paper III)

Paper III takes a closer look at the part of road tunnel fire safety aimed at estimating fire life safety, i.e. requirement two above, and the means for a safe evacuation. The purpose was to investigate the accuracy and applicability of tunnel fire dynamic models for road tunnel fire risk analysis. Tunnel fire dynamics theories have evolved over the last fifteen years (see for example Ingason et al. 2015). Despite the simple symmetry of tunnel tubes with longitudinal ventilation where the smoke primarily moves in one direction, complex and resource intensive computer fluid dynamics calculations are applied for road tunnels. The aim of this paper was thus to investigate the possibility to apply one-dimensional fire dynamics theory in relation to performance of a risk analysis.

Equations for the time until tenability becomes compromised were derived for gas temperature (T), smoke stratification, incident heat flux (*q"*), visibility (V) and gas concentrations (X). Critical values for tenability were derived from literature and the time until they were reached was calculated. The modelled time to compromised tenability was compared with experimental data from eight tunnel fire experiments (Ingason and Lönnermark 2004, Lönnermark and Ingason 2007, Ingason et al. 2011, Lönnermark et al. 2012), see Table 2.

Table 2 Data of the eight tests that were used from three tunnel fire experiments.

	Runehamar				Model-scale tunnel			Arvika
	T1	T2	T3	T4	T1	T7	T10	T3
Fuel	82% Wood, 18% PE	82% Wood, 18% PUR	70% Wood, 30% PUR	81% Paper & Wood, 19% PE	Heptane	Wood	72% Wood, 28% PE	Train wagon
Peak HRR (MW)	202	157	119	66	0.146	0.113	0.114	75
Air velocity (m/s)	2.2	2.9	3.0	3.0	0.67	1.12	0.67	2.77
Cross-section area (m^2)	47.4				0.1125			42.1
Perimeter (m)	30				1.4			26
Measurement position (m)	+458				+3.85 (77 in full scale)			+100

If the critical value was not reached for at least one of the measured or calculated values, the time when 80% of the maximum value is reached was used (shown in grey in Table 4). This is a practical compromise since at least 80 % was reached in all tests. Input model parameters were classified in three groups: #1 known input parameters that were measured in the experiments, e.g. fire size as a function of time, or #2 constants that were considered to be certain, e.g. molecular weights, or #3 constants that were uncertain, e.g. yields, effective heat of combustion or optical smoke density. The uncertainty was represented by uncertainty intervals, see Table 3. In Table 4, the sensitivity to variation in these uncertain input parameters is represented by the minimum and maximum value.

For most parameters and tunnel fire tests, the sensitivity to variation in the input parameters was low, i.e. it had a small effect on the time to compromised tenability. However, for fires without a steady fire growth rate, the sensitivity can be very high, e.g. in the Arvika fire test (METRO project) where the fire was steady for a very long period of time before it started to rapidly grow after 110 minutes (Ingason et al. 2012). In such cases, the targeted value could be reached at the start or end of the fire within the range of input values. Any fire safety model would be sensitive to the fire growth rate. Nevertheless, in risk analysis good praxis is to stay on the conservative side which means that a steady fire growth rate (until the peak HRR value) will be selected.

Table 3 Input data with uncertainty intervals used for the sensitivity study.

	Runehamar				Model-scale tunnel			Arvika
	T1	T2	T3	T4	T1	T7	T10	T3
CO yield (g/g)	0.058 ±20%	0.011 ±20%	0.089 ±20%	0.058 ±20%	0.061 ±10%	0.058 ±20%	0.059 ±20%	0.089 ±30%
CO_2 yield (g/g)	1.8 ±20%	1.7 ±20%	1.7±20%	1.8±20%	2.9±10%	1.6±20%	2.0±20%	2.1±30%
HCN yield (g/kg)	0.011±20%	0.33 ±20%	0.56 ±20%	0.011 ±20%	0.018 ±10%	0.010 ±10%	0.012 ±20%	0.60±30%
H_{ec} (MJ/kg)	17.1 ±20%	16.4 ±20%	18.9 ±20%	17.3 ±20%	41.4 ±10%	12.4 ±10%	19.7 ±20%	25±30%
D_{mass} (m^2/kg)	73 ±20%	81±20%	110 ±20%	74±20%	190 ±10%	38±10%	92±20%	[127;407]

The Froude expression (Ingason 2012) used to estimate the stratification did not agree well with experimental data. Since this study was performed, the Froude number correlation has been further developed (see Ingason et al. 2015). In the study, other smoke stratification indicators, e.g. temperature and visibility, from the experiments were used instead. The modelled values of all other tenability indicators, e.g. CO, CO_2 gas concentration, temperature and visibility, agreed to within 10-20 % of the experimental data.

The repeatability of fire experiments can vary considerably, a good example is the train tests carried out within the METRO project (Lönnermark et al. 2012) where the fire grew very slowly for a long period of time in one of the tests. The trains were identical, but the lining material was prepared differently in the tests, one with a lining barrier and one without. When the fire spread through the lining barrier the fire growth was nearly identical, but totally different prior to that. In the model comparison of Paper III, the measured HRR is compared with the experimentally recorded time to compromised tenability. Under such conditions, the variability between fire tests is less relevant since the measured HRR is strongly coupled with other measured data in the same experiment. The error in the hardware for fire temperature measurements is reported to be ±0,4 %, and ±1 % for gas analysis equipment (Andersson 2009). The error in single Cone Calorimeter HRR measurements is in the order of 10 % (Axelsson et al. 2001). Measurement accuracy can be compared by looking at two similar experiments. If the HRR, and all other experimental parameters are the same, similar temperature, visibility and gas concentrations should be recorded. Not all test series have two similar HRRs, which means measurement accuracy, given the same HRR is unknown. Model scale experiments test 2 (0.832 kg wood) and 9 (0.806 kg wood) have, apart from slightly different amount of wood, the same experimental conditions. We would therefore expect, e.g. the temperature and oxygen measurements to be similar, see (Lönnermark and Ingason 2007), which they are. The uncertainty in measured data is in the same order of magnitude (10 %) as the difference between measured and modelled output (10-20 %). This means that a higher accuracy is difficult to achieve.

To summarize, considering the uncertainties in engineering models and risk analysis that often is several orders of magnitude, accuracy at 10-20 % is sufficiently good and a small source to the overall uncertainty from assumptions concerning human behaviour, fire growth rate and associated probabilities.

Since visibility becomes critical first for limit-based models, a simple mathematical expression for available and required safe evacuation calculations was derived. The main weakness with the proposed model is the cases when smoke stratification is significant, i.e. at low ventilation velocities. In bidirectional road tunnels a fire safety concept is to keep the smoke stratified by a minimal amount of ventilation.

Table 4 Results from the comparison between modelled times to compromised tenability and measured from tunnel fire experiments. If the critical value was not reached for at least one of the measured or calculated values, the time when 80% of the maximum value is reached was used (grey cells).

Tenability criteria			Runehamar								Model-scale tunnel						Arvika		
			T1		T2		T3		T4		T1		T7		T10		T3		Average
			Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	Time (s)	Rel. diff.	rel. diff.
V = 10 m		Measured	434		320		268		366								165		
		Minimum	360	17.1%	313	1.6%	246	7.5%	306	11.5%							35	-	**9.4%**
	Calculated	Maximum	360		317		250		330								6457		
		Mean	360		315		248		324								5432		
XC02 = 65000 ppm		Measured	701		892		592		504		372		83		111		7238		
		Minimum	1129	4.3%	762	14.6%	552	6.8%	500	0.8%	392	1.6%	95	14.6%	137	12.7%	7002	3.3%	**7.3%**
	Calculated	Maximum	631		762		552		500		371		95		72		7002		
		Mean	671		762		552		500		379		95		97		7002		
XC0 = 1550 ppm		Measured	530		858		360		411		221		62		55		6935		
		Minimum	639	5.3%	762	11.2%	552	53.3%	500	21.7%	374	64.4%	76	1.6%	83	9.2%	7017	0.8%	**20.9%**
	Calculated	Maximum	506		762		552		500		358		52		52		6846		
		Mean	558		762		552		500		363		61		60		6990		
X02 = 12%		Measured	937	7.5%	852	10.6%	585	5.6%	506	1.2%	366	2.5%	81	17.4%	108	6.5%	7087	1.2%	**6.6%**
		Calculated	1007		762		552		500		375		95		101		7002		
XHCN = 105 ppm		Measured	517		403		322		475										
		Minimum	954	84.5%	762	89.1%	552	71.4%	500	5.3%									**62.6%**
	Calculated	Maximum	954		762		552		500										
		Mean	954		762		552		500										
q" = 2,5 kW/m²		Measured	751	25.4%	563	70.5%	522	13.8%	508	10.8%	368	2.4%	142	41.1%	157	44.6%	7072	1.1%	**26.2%**
		Calculated	942		960		450		453		359		84		87		6997		
(5) Tfl = 60°C		Measured	738		1110		831		676		237		79		79		7083		
		Minimum	678	8.1%	475	57.2%	543	34.7%	500	26.0%	112	52.9%	45	42.1%	47	40.8%	6878	2.9%	**33.1%**
	Calculated	Maximum	678		475		543		500		112		45		47		6878		
		Mean	678		475		543		500		112		45		47		6878		
(3) Tfl = 60°C		Measured	738		1110		831		676		237		79		79		7083		
		Minimum	890	14.5%	505	62.8%	570	44.5%	500	26.0%	78	63.5%	36	51.1%	38	44.7%	6831	3.6%	**38.8%**
	Calculated	Maximum	579		395		417		500		112		39		47		6830		
		Mean	631		413		461		500		87		38		44		6831		

4.4 A fire safety design framework (Paper IV)

In Paper I - III the basis for a performance-based design of road tunnels in Sweden, combined with evaluation of models that can be used, was established and a design guide was developed. The journey about how fire safety in road tunnels should be ensured and dealt with moves now on to critically examine fire safety performance-based design and to explore alternatives. A design framework consists of a theoretical framework which points to a set of suitable methods which in turn are applied to solve design problems. Based on an understanding of fire safety design from the literature and interviews, a design framework has been developed. Several challenges for fire safety design were identified earlier in this thesis, through interviews with tunnel fire safety professionals, and in Paper I & IV, these are summarised as follows:

- The view of safety as something absolute that is either acceptable or not acceptable and the practice of defining safety levels for each objective in isolation (limit-based design).
- The practice of limiting performance-based design to the evaluation of one alternative that is verified as “acceptable”.
- That neither limit-based, nor CBA-based design emphasise the quality of solutions or encourage creative or innovative solutions, i.e. maybe better goals or objectives could be achieved.
- That the fire safety problem is turned into a separate problem where mainly quantitative factors matter.

The dual nature of risk as a potential for physical damage and as a social construction demands a dual strategy for safety design. Technical expertise can assess the magnitude and likelihood of risks, but public input is needed to set priorities and objectives. The whole procedure for decision-making should be emphasized and allow for a fair involvement of stakeholders in the whole decision-making process. Stakeholder could be a person, group or organization that has interest or concern in the fire safety design, e.g. legislative bodies, rescue service, owner and users. Ethical factors and moral values are relevant knowledge, necessary to make rational decisions. The fire safety design framework should be based on intermediate methods between hard and soft systems methods. Rational risk evaluation takes a middle way between cultural relativists and naive positivists, and both the scientific and ethical/democratic components of risk need to be acknowledged.

All knowledge and experience of FSE as a field and among fire safety engineers is included by the theoretical framework, with an awareness of the limitations of limit-based and CBA-based design. Safety is seen as being relative and tradable with other objectives, which makes the proposed theoretical framework incompatible with a strict limit-based design approach where safety is not traded. Risk analysis will be needed to analyse consequences for safety objectives. CBA will be needed to analyse cost factors that can be quantified. Methods that can include all factors in the proposed theoretical framework are more general decision or design methods. The question of how safe a road tunnel should be is then reframed into a problem-solving setting. Once this has been achieved, the tools from decision-making can be used to structure the problem, to remove constraints and biases, to identify the key objectives and potential solutions, to evaluate solutions and to identify trade-offs. The fire safety problem is reframed into: *finding the best solution to stakeholders' decision objectives and priorities.* Indeed, it may not even be relevant to talk about "how safe should the tunnel be" because it is subordinate to the overall decision condition, once all aspects have been considered.

It is further argued that a shift towards Vision Zero offers the best prospect for innovation and creative solutions. In the Vision Zero design philosophy, certain qualities should be engineered into the system; safety should be an inherent property or, at least, the system must fail safely. This sets higher or at least different requirements than what is typically analysed and engineered in limit-based or CBA-based design. It is not good enough to engineer an acceptable or a safe enough solution but instead the aim is to achieve a close to absolutely safe system, or a system that is forgiving to human errors and mistakes (excluding e.g. violations). Given that society wants improved safety, then Vision Zero emerges as a powerful strategy. Other aims such as cost, and feasibility are also included in the decision process.

It is argued that, by including the whole decision process, rather than risk analysis or FSE used to verify *one* solution, the quality of the decision can be ensured. Thus, fire regulation should include the whole decision process, e.g. specify the roles and knowledge of different stakeholders and the objectives that might be relevant, including also moral factors to ensure fairness and a balance between conflicting objectives.

To address the challenges summarized above, a design framework with a set of methods was proposed:

- A decision-making framing to find the best solution according to stakeholder objectives and priorities (both quantitative and qualitative factors, both technical and ethical or democratic aspects).
- A general iterative decision-making process with the following phases:
    - Problem framing and reframing.
    - Development and refinement of decision objectives to aim at.
    - Creative generation of alternatives that solves the problem (i.e. best achieves all objectives).
    - Consequence & uncertainty analysis of how well the alternatives achieve the objectives.
    - Evaluation and trade-offs to find the best alternative (for the design group and stakeholders).
- A view of safety as something relative; relative to the decision objectives and values of stakeholders. The owner, design team and other stakeholders know the values and priorities for making the best decision or trade-off in each decision.
- Decision-making theory should drive the process and highlight where analysis matters most.
- High ambitions through a Vision Zero design philosophy (in particular to derive solutions that have the quality of being inherently safer or fail-safe).

The design framework of Paper IV could be applied to any fire safety decision, e.g. buildings. The next chapter investigates how fire safety in road tunnels is designed and how the proposed framework could be applied to this design problem.

5 Applying the proposed design framework to road tunnel fire safety

In this chapter the design framework derived in Paper IV is applied to road tunnel fire safety. In particular a general decision-making method is applied to a Swedish road tunnel fire safety design context. The chapter starts out with a description of the Swedish road (tunnel) design process today, which is also analysed. It is proposed how the design framework fits into the planning and design process. Interviews with tunnel fire safety professionals were used to better understand the application to real problems. The aim of the following sections is to highlight not only safety objectives but also other objectives that can conflict with, or strengthen, safety. Further, they aim to exemplify how safety objectives can be measured, what conflicts might exist and how these can be evaluated in a decision-making process. The design framework then assumes that the tunnel fire safety regulation is performance-based so that the project and fire safety design team have complete freedom to choose the best solutions.

5.1 Fire safety design of Swedish road tunnels today

The planning and design process of Swedish road tunnels was investigated in a project for the Swedish Transport Administration in 2010-2012 (Gehandler et al. 2012a, Gehandler et al. 2013). Interviews with tunnel safety professionals was also performed at different occasions within the scope of this thesis work, see section 3.2.

Swedish laws and ordinances are published in the Swedish Code of Statutes (SFS). Planning and construction of roads in general that may or may not include road tunnels are principally regulated in the Road Act (SFS 1971:948), the Swedish Environmental Code (SFS 1998:808) and the Planning and Building Act (SFS 2010:900). In the Road Act the planning process is outlined, including requirements for consultation with agencies, municipalities, the public and other stakeholders. The County Administrative Board (Länsstyrelsen) decides if an Environmental

Protection Assessment (MKB – Miljökonsekvensbeskrivning) is required for the project. An MKB aims to minimize the environmental impact of building works, including also health and other laws, e.g. fire safety. There is a formal work process for an MKB. Fire safety is not explicitly treated but is considered as one of many health issues. According to the Environmental Code trade-offs between conflicting objectives should be performed such that long-term sustainability is achieved. The County Administrative Board is an important stakeholder within the MKB work since they approve the project based on the MKB. In the approval, the County Administrative Board can set up certain requirements or conditions for the project. Larger projects are also approved by the government who likewise can set up requirements or conditions for the project. The Planning and Building Act and Ordinance regulate the planning process for building works and deal with fire safety in a general manner, stating that the building works shall have safety measures to provide a sufficient safety level concerning life safety and prevention of fire spread and smoke spread within the building works.

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 Ordinance on Safety in Road Tunnels (SFS 2006:421) further specifying the minimum requirements for fire safety. At the lowest formal regulatory level the Swedish Transport Agency[2] (Transportstyrelsen), has issued mandatory provisions on safety in road tunnels (TSFS 2015:27). These provisions are requirements further explaining the minimum level of safety in tunnels longer than 500 m. The TSFS provisions require that each tunnel above 500 m should have a safety officer who shall coordinate all preventive measures and safeguards to ensure the safety of users and operational staff. The TSFS provisions are on the same legal level as specific requirements for buildings (not applicable to road tunnels) issued by the Swedish National Board of Housing (BBR26 2018). Road tunnels are also exempt from the approval process in the Planning and Building Act and Ordinance. The Swedish Transport Administration (STA – Trafikverket), have developed their own road tunnel design guides to facilitate the management of tunnel projects since the 1990s. These are not mandatory but apply, with or without changes, when they are referred to in contractual agreements between the STA and building entrepreneur.

National rules and design guides have lately been applied to many large tunnel projects. Therefore, Häggström et al. (2016) argue that stakeholders now have a clear picture of a prescriptive tunnel solution, called ‘base-tunnel’. The base-tunnel is a reference fire-safe road tunnel. In these larger road tunnel projects, a quantitative

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[2] The Swedish Transport Agency is not to be confused with the Swedish Transport Administration which is referred to as STA in this thesis.

risk analysis is often carried out. However, it is not clear how the risk output should be evaluated, as an acceptable risk level for Swedish road tunnels is missing. Lately, research projects have been launched by The Swedish Transport Agency to define such a level. Malmtorp et al. (2014), suggested that the risk should be similar to surface roads. Later Häggström et al. (2016) suggested an ALARP region normalised per person km for all Swedish transportation tunnels. Risk analysis and ALARP should then be used to justify deviations from the base-tunnel (Häggström et al. 2016). This development has not yet resulted in any changes in the national tunnel regulation.

Most road tunnels in Sweden are built by STA or the City of Stockholm. The construction of a road or a tunnel is often preceded by a lengthy process affected by many different policies, rules or regulations, local, regional or national politics and the opinions of various stakeholders. Swedish tunnels and roads have a similar planning and design process since STA often are responsible for both. Prior to 2013, this planning and design process contained four stages: pre-study, road-study, road-plan and technical specification, see Figure 7. In 2013 the three stages pre-study, road-study and road-plan were replaced by a more coherent planning process; however, the content is similar to the previously separate stages. Since much available information about road tunnel fire safety design relate to the previous three stages, they are still used in this thesis to indicate where in the planning process one is (Trafikverket 2014:144).

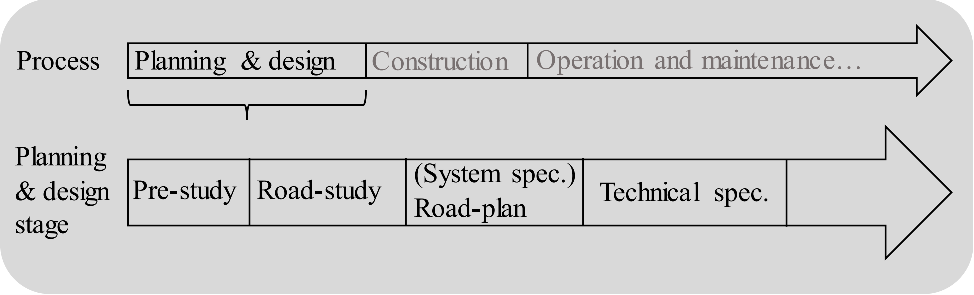

Figure 7 Design stages during the planning and design of a road tunnel.

In the pre-study, the main question is whether a road connection should be made between points A and B. Aspects such as mobility, safety, accessibility and the environment are evaluated. If it is decided that a new construction is necessary, a suggestion of a geographical area and a description thereof is made. Information concerning road tunnels can be sought if that is an option. In this stage a safety concept should be established. In negotiation with affected stakeholders, STA decides whether the project should continue or not.

In the road-study stage different possible corridors for the road are evaluated. Advantages and disadvantages with different alternatives are compared with the alternative to do nothing and the alternative to improve existing infrastructure. The aim is to solve the identified problem with the least environmental impact, for this purpose an MKB according to the Swedish Environmental Code is most often required. It is mainly STA and concerned municipalities that decide which alternative that is best. The safety concept is further developed and decided. The safety concept includes the means for self-rescue and the rescue service intervention. The winning alternative is sent for approval to the government. It is by now decided whether a tunnel is needed or not. A safety goal should be derived together with concerned stakeholders and a safety officer should be selected by the client and approved by The Swedish Transport Agency. If the government approves the plans the project enters the road-plan stage.

Before the road-plan stage a system specification is often needed. This specifies the technical systems that will be needed and what physical space the system or systems require. The tunnel is planned in greater detail in this stage and the chosen corridor is evaluated against existing regulation (in particular the Environmental Code). For tunnels, this is the point in time when the fire safety design takes more concrete shape. At the end of the road-plan stage a preliminary design can be seen to exist.

In the technical specification stage, it is specified in detail how the tunnel should be built and how all systems should function and communicate so that entrepreneurs can bid to win the construction contract of the tunnel. The technical specification stage is not mentioned in any regulation and cannot be appealed. This stage can be undertaken by another group of tunnel safety professionals than that employed during the road-plan stage.

As one of the interwiees expressed, following the negative environmental impact in terms of drained wells and poisoned surface water during construction of the Hallandsås tunnel and the severe alpine road tunnel fires, road tunnel safety has become a top priority. A tunnel project consists of many different branches such as fire safety, installations and construction. Since knowledge about fire safety and risk often is limited within the client organization, e.g. STA or City of Stockholm, ordering support for fire safety is purchased by the client, see Figure 8. Early in the project the fire support helps the client to develop a safety goal in negotiation with stakeholders. Such a goal can, for example, specify more general principles such as avoidance of catastrophes, that reasonable safety measures are used, cost lies in proportion to benefits, fairness, or continuous improvement and quantitative road user criteria for individual and societal risk is considered. Often the safety target is based on a safety concept or even a reference tunnel in compliance with regulation, design guides and best praxis which sets the standard for fire safety. With help from the fire support the client procure a fire safety design team to the project, see Figure 8. Note that the load-bearing capacity in the event of fire is primarily dealt with by another design group focused on the overall load-bearing construction, described below.

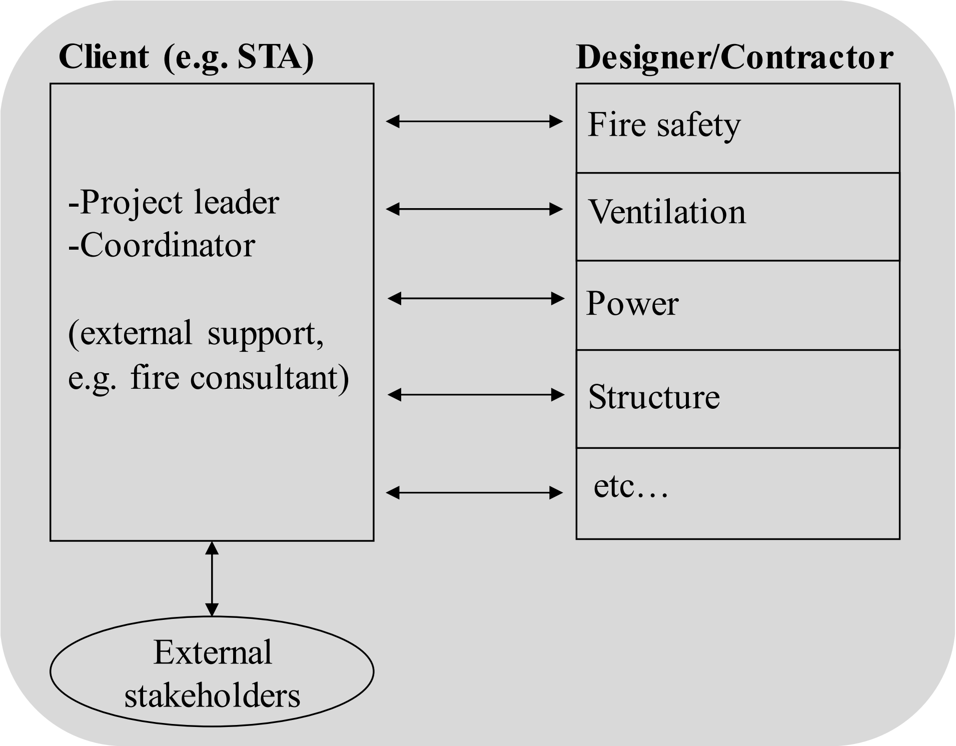

Figure 8 Overview of a road tunnel fire safety design project. A fire safety design takes shape in negotiation with the client and their fire support, other instalations and external stakehodlers.

Based on the performed interviews, it is clear that risk management is a central activity throughout the planning and design stages. Many qualitative and quantitative risk analyses are performed. Risk analysis should support design decisions. Risk management along the project is regulated in the MKB work, tunnel safety regulation and through internal guidelines from the STA. The purpose is to ensure coherence from planning and design to construction and operation, i.e. to ensure that risks are managed and that no risks or safety concepts are misinterpreted when they are handed over, e.g. from the design stage to construction or operation, or from one design branch to another. This is mainly achieved by safety documentation and an appointed safety officer who coordinate the risk management activities. Based on the risk analysis, risk evaluation is performed by the fire safety design team with the client and other relevant design branches at meetings (i.e.

either work meetings or decision meetings (a higher-level meeting)). Risks can either be accepted or managed. Along this process, risks are managed in different ways. Early in the project, land usage, e.g. the choice of geographical area in the pre-study stage or corridor in the road-study stage, can be one way to control risks. Later in the project technical risk measures or risk transfer to responsible parties can be used. Continuously along the process consultation meetings are also arranged by STA with external stakeholders such as the public, rescue service and third-party reviewers. The idea with the consultation meetings is that the project can obtain help with risk evaluation and tough trade-offs. However, at least some of the interviews reveal that these meetings often are experienced as a one-way communication where the STA gives information about the project. Figure 8 aims to visualize how a fire safety design is negotiated with the client (work and decision meetings), other design branches (work and decision meetings) and external stakeholders (consultation meetings).

The fire safety design team should find the best solution according to the client´s specifications. For life safety, the interviews reveal that these may be more or less well defined early in the project, e.g. through a safety goal and a safety concept. There seems to be a trend towards well defined safety targets early in the process. Such early safety targets, safety concepts or reference tunnels limits the freedom of the design team in their quest to find the best solution during the project when many systems take more concrete form and evolve with other branches of the project. Their work can then be described as a zig-zag process between problems and solutions, as several interviewees described it, see Figure 9.

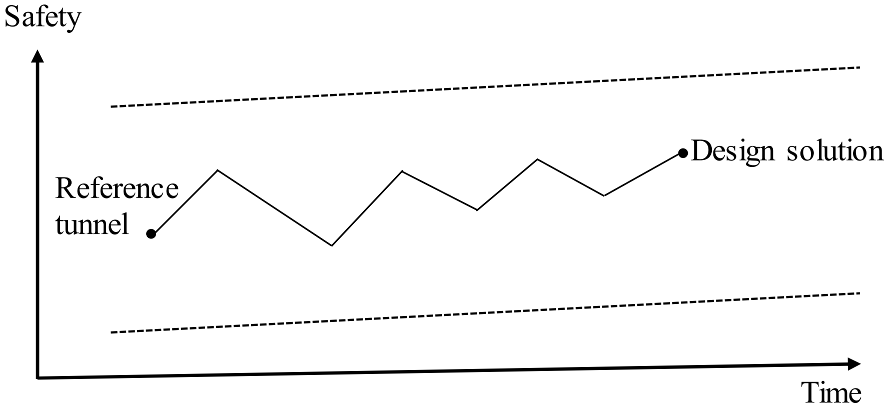

Figure 9 Schematic diagram of the solution space for the design solution. The design starts from a reference tunnel or safety concept. Along the project, the design zig-zag between problems and solutions within the defined safety target. Safety should continually improve.

The solutions are discussed with the client and it is verified that the solution stays within specified safety limits. The quantitative criteria emphasize quantifiable factors for a set of possible accident types (fire fatalities). It can be possible to trade safety with other conflicting objectives such as cost, environmental protection, future management and operation, although the client is often uncomfortable making such trade-offs. All interviews reveal that the knowledge for doing such evaluations are limited and the goals and values of the organization are not explicitly communicated. Instead fire safety is treated in a separate process (according to the safety goal and its means for assessment if this has been defined). This means that other objectives, e.g. availability or security, that may conflict, become “invisible”, as one interviewee expressed it.

One of the interviewees was working on the load-bearing capacity in the event of fire for rock tunnels, which is actualized during the road-plan or system specification phase as an integral part of the overall load-bearing construction process. Fire has never resulted in a collapse, but the fires in the Eurotunnel and Mont Blanc tunnel resulted in severe damage to the concrete lining. It is assumed that society cannot tolerate the collapse of the tunnel or, for the owner, that extensive rock fall is not tolerable. For most tunnels that the STA build, they are also the future tunnel manager. It is therefore in their interest that the tunnel handles a fire sufficiently well. Rock tunnels are dimensioned by protecting the load-bearing system, e.g. with spray concrete or insulation, to ensure that the system have sufficient load-bearing capacity despite the fire load. For rock tunnels a concept of different categories of rock strength is defined. Strong parts of the tunnel are determined “category 1” parts of the structure while weaker parts are designated “category 2”. Only the weaker parts of the tunnel (Category 2) are protected, typically around 10% of the tunnel. Stronger parts (Category 1) are not protected because the rock is strong enough to avoid collapse or extensive rock fall. Since regulations are lacking at a higher level, STA guidelines become design guidelines (Trafikverket 2014:144). Design fire loads for rock tunnels are found in The STA design guides in terms of time-temperature curves. They are relatively conservative, e.g. the hydrocarbon (HC) curve with a duration of 120-180 min. The choice of temperature curve is directly connected to the investment costs. Since these are internal guidelines, they can be modified to fit the actual situation. This internal decision-making process at STA is important for the design but is not clearly described or formalized. How the time-temperature curve is determined is project-dependent. It is often based on the guideline, but departures can be made in consultation with fire consultants. Fire consultants are then consulted for a "worst case", or "maximum heat load", time-temperature curve for use in systems design for the current tunnel usage. In some cases, projects may decide to implement the ISO curve instead. In this process there is no balancing of cost or other objectives such as the environment. For heat transfer calculations, fire consultants are consulted once again to determine the thickness of the chosen protection. They are instructed to account for the heat transfer that continues after the time-temperature curve stops. The Eurocode (EC7) is not always applicable to rock tunnels, but some parts, such as partial coefficients, can sometimes be applied, see (Trafikverket 2014:144). In the next section the Swedish road tunnel design process is briefly analysed.

5.2 Analysis of the tunnel fire safety design process

In this section the Swedish tunnel fire safety design process outlined above is discussed. It starts out with other studies of how tunnel fire safety should be dealt with. In 2002 STA released a report on how tunnels should be designed. A linear process with the following steps was outlined (Vägverket 2002):

1. quantifiable requirements,
2. conditions for assessment,
3. assessment that shows that the requirements under the given conditions are met,
4. control, and
5. monitoring.

Based on the interviews, this way of thinking is still prevalent, perhaps taken a bit too far when quantifiable requirements are stated very early when only a tentative design exists which isolates the fire safety design process from the overall project.

In 2005, due to a general perception of large variation and uncertainties concerning the treatment of tunnel life safety issues in recent tunnel projects, the government commissioned four concerned authorities (Räddningsverket, Banverket, Vägverket and Boverket) to study how life safety in tunnels should be dealt with (Boverket 2005c). Excluding guidelines, e.g. from STA, all applicable regulations must be fulfilled, with no single law having president over another, i.e. they are all simultaneously applicable. The study concluded that tunnel life safety regulation should be based on verifiable performance-based requirements. Prescribed solutions and methods for assessment should be optional. It is, however, not possible to see a transition towards performance-based requirements in tunnel safety regulation, design guides, or recent projects. Such a structure was the aim of RO1 which resulted in the design guide behind Paper II. The governmental project further concluded that the national goals for transportation should be guiding also for life safety issues. Other important goals are cost, availability, the environment and a long-term perspective. Also worry and perceived safety should be included in the MKB work (Boverket 2005a). The study argues that questions about life safety should be raised early in the planning process. Stakeholders should discuss and agree on how risk evaluation should be dealt with along the project. Life safety and risk issues comprising both likelihood and consequence should be included in the MKB work. The environmental consequence from safety measures should also be included in the MKB work (Boverket 2005a, Boverket 2005c). It could very well be that road tunnel safety measures, e.g. life-cycle assessment (LCA) impact from materials, cause a larger environmental impact, e.g. CO_2 emissions than the life safety benefit, but this is generally not evaluated today.

The following paragraphs summarize the main challenges in the Swedish road tunnel fire safety design process and argues for how the proposed design framework could address identified challenges. The Swedish road tunnel design process is a formalized process laid out in the Road Act and the Environmental Code that includes many stakeholders and objectives. However, fire safety is not always an integral part of this process and, fire safety is not often traded with other objectives as is proposed in the process of the Environmental Code. A historical reason for this is that design values in regulation and design guides have evolved through a mixture of experience and expert opinions. Risk levels are sometimes defined on-top of the consequence-based limits, which makes the purpose of the analysis unclear. Once defined, the limits and loads are not affected by any other objectives, which makes fire safety an isolated process. If holistic or integrated fire safety design is to be encouraged, regulation and design guidelines need to allow for performance-based design. Then consequence-based limits and loads need to be removed or turned into an optional recommendation. Instead the function and purpose of the rule should be achieved in relation to other objectives.

Many of the interviews reveal that two of the stronger principles in fire safety design are avoidance of catastrophes and constant improvement. Tunnel fires are considered to be a potentially catastrophic incident. Future road tunnels should be equally safe or, preferably, safer than existing ones. It may be that this tradition now has taken road tunnel fire safety to a very safe state, much safer than many other parts of the road network, as is argued by Bowman (Bowman 2018). Up to this point, real consequences from fires are negligible compared to traffic accidents, e.g. no tunnel fire casualties have occurred in Sweden so far. One may very well ask whether the fire safety pendulum has not swung too far; what reasonable mechanisms could provide greater balance between fire safety and other design criteria, see Figure 10? Although risk analysis is performed and ALARP criteria are defined, the interviews reveal that the practice of performing trade-offs with other objectives or cost-benefit evaluations are still limited.

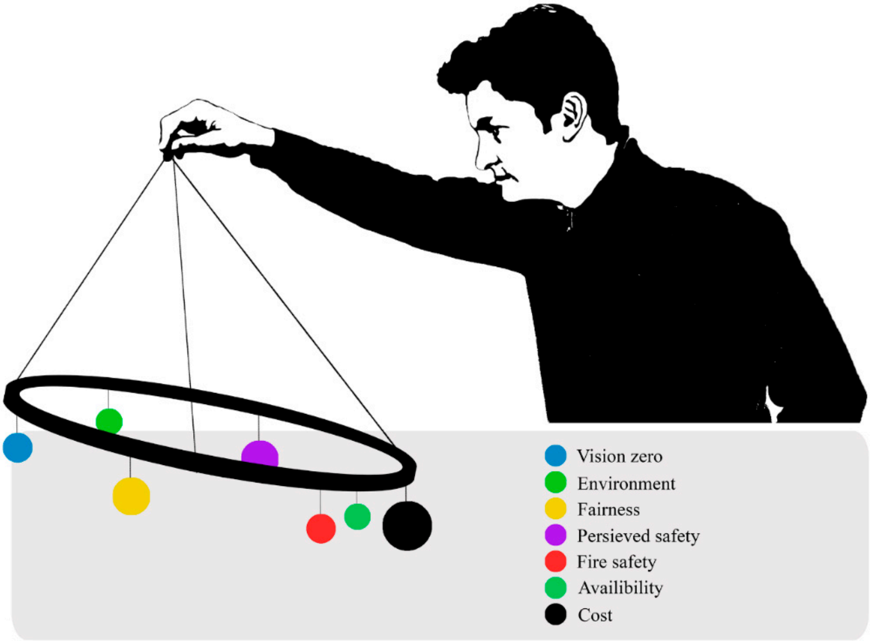

Figure 10 Have fire safety in road tunnels gone too far? How can it be balanced? (Illustration: Mats Molid).

I argue that a decision-oriented approach gives the necessary framework for weighing other objectives against safety. An iterative decision-making process consisting of the following five main stages is proposed in Paper IV: #1 problem framing, #2 objectives, #3 development of alternatives, #4 consequence & uncertainty analysis, and #5 risk evaluation & trade-off, outlined in Figure 11. The way the problem is stated frames the decision and determines what can be regarded as solutions. Objectives specify all the concerns that the decision must address. Alternatives are the different courses of action available to choose among. The decision can be no better than the best alternative. Next, consequences from each alternative are evaluated for each objective. Often objectives conflict with one another, which is why trade-offs are inevitable. A decision-oriented approach requires knowledge about fire safety and risk, discussion of organizational goals and an agreement among stakeholders for making trade-offs. Such an agreement could be made between concerned stakeholders early in the project, and fire/safety/risk consultants could support the client with necessary knowledge in the decision-making process. Values to set trade-offs and priorities need to be communicated within and between concerned stakeholders, e.g. at the consultation meetings. The next section aims to clarify where and how the proposed design framework fits into the tunnel design process.

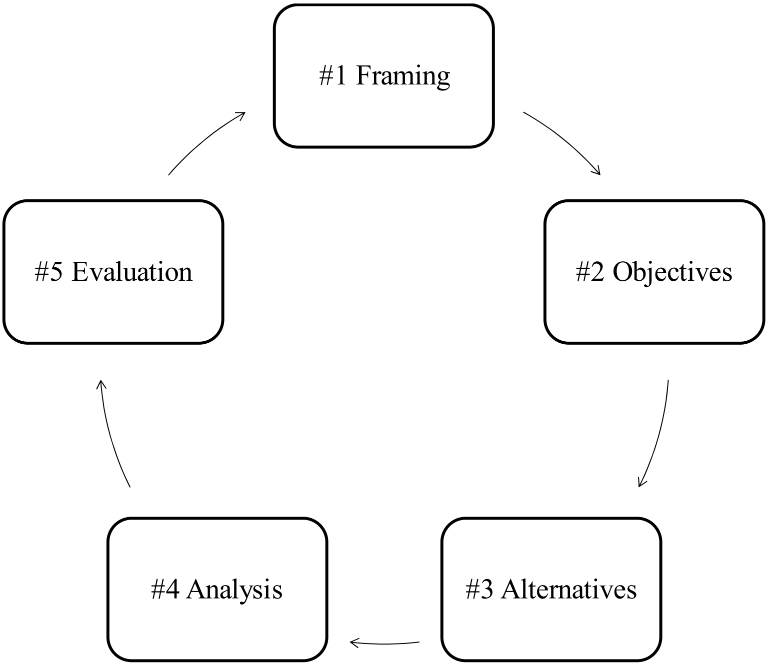

Figure 11 The five phases of the iterative decision-making process.

5.3 Application of the proposed design framework

The developed design framework with its explicit emphasis on the decision-making process fits well into the MKB process where conflicting objectives of the Environmental Code, concerned stakeholders and other applicable laws should be weighed against each other. This means that relevant quantitative and qualitative objectives already emerge in the MKB work. What is sometimes missing is that the fire safety design process should become an integrated part of the overall MKB process and infrastructure project. Inherently safer solutions are most likely derived during the early stages. Therefore, road safety knowledge should be part of the pre-study and in particular road tunnel fire safety knowledge as soon as road tunnels start to be discussed in the road-study stage. Early in the project it is most likely the client who runs the fire safety design process with the procured fire support. In the road-plan stage a fire safety design team will be procured to assist the project.

The main difference compared to a traditional approach, is that the proposed design framework excludes a limit-based design approach. To maintain design freedom and the possibility to choose the best solution during the whole design process, the project should refrain from any definition of exact safety limits, i.e. no limit-based design approach. Note that this does not exclude analysis; how well trial alternatives achieve objectives should be analysed qualitatively and quantitatively. However, how much we want is better evaluated towards the end when we have all the information on the table rather than at the start of the project. Any tentative design at the start should not be considered to be a reference for a safe tunnel. It is of course the ambition that safety is increased, which is the purpose of Vision Zero, but one should also be open for the possibility that safety, in relation to other objectives, could to be reduced. Consultation meetings in particular and communication in general with the client and other stakeholders will be important to strike the best balance between different trade-offs. Documentation during the planning and design stages will be important to ensure coherency throughout the design process.

In the following five sections, the decision-making process in Figure 11 is outlined from phase one to phase five for a general road tunnel case. It is then assumed that rules and regulation are performance-based.

5.3.1 Problem framing

Framing the problem correctly drives everything else. The way the problem is stated frames the decision and sets the boundaries for results that can be regarded as solutions. Problem framing evolves along the iterative decision-making process. The context for this general decision is that we have a planned road tunnel for which fire safety needs to be engineered. Rather than formulating the problem as one of achieving an acceptable level of safety (i.e. limit-based design), or enough safety (CBA-based design). The problem is framed as a more open decision-problem aimed at finding the best solution, given stakeholder objectives (quantitative and qualitative) and priorities. This methodology is in accordance with that presented in Paper IV. It may not even be relevant to talk about "how safe should the tunnel be" because it is subordinate to the overall decision conditions, all aspects considered. Most likely the design group starts with a tentative design which will become the first status-quo alternative below. Two important questions for the problem framing concerns the two possible movements in the space of alternative designs; 1) are there some objectives which are poorly dealt with?, or the opposite, 2) is the trial design too conservative concerning some objectives, e.g. is it too safe? The aim is to achieve a road tunnel fire safety design in proportion to other identified decision objectives, see Figure 12. Decision objectives are derived in the following phase.

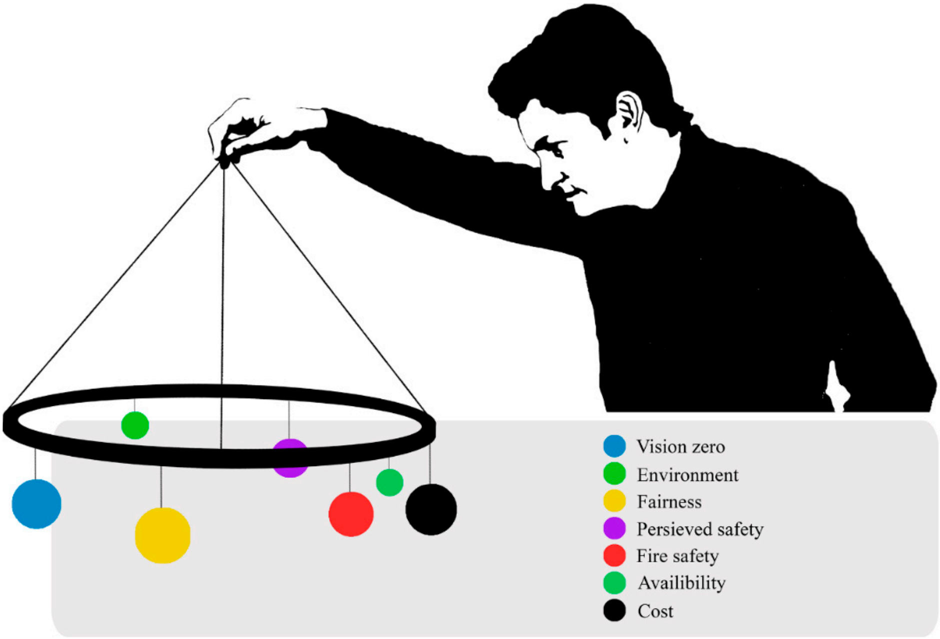

Figure 12 A balance between road tunnel fire safety and other relevant decision objectives (Illustration: Mats Molid).

5.3.2 Decision objectives

Decision objectives specify the goal of the decision. Objectives can be identified by specifying all the concerns that the decision must address. General ethical, political and societal objectives with a bearing on safety and risk evaluation have been derived from literature, including scientific articles, regulations and policies.

The overall aim of a fire safe tunnel is broken down into five key objectives in Paper II, see objectives 1 to 5 below. These objectives were developed in a Swedish context but can be derived from the EU construction products directive (CPR 2011) and EC directive on minimum safety requirements for road tunnels (2004).

STA has the following goals from the Swedish government: Ensure an economically efficient and long-term sustainable provision of transportation, which benefits both industry and citizens throughout the country. Availability with regard to usability for all road users and mobility is a performance goal. Safety, the environment and health should be considered (Trafikverket 2011). According to the Swedish Environmental Code that applies when tunnels are to be built, valuable natural or cultural environments should be protected. These goals (objective 6-8 below) are general and likely to be valid for most countries (Johansson 2011).

A fair distribution of risks and benefits is a central ethical risk issue to justify why someone may be exposed to a risk (Hermansson 2005, Hermansson and Hansson 2007). As children, young adults, and the elderly are disproportionately exposed to traffic risks, Hokstad & Vatn (2008) argue that fairness (objective 9 below) rather than utility should be the guiding rule for resource allocation.

Large road tunnel fires are sometimes labelled as ‘catastrophic’ (Leitner 2001, Ingason 2003). Presumably, societies have an aversion to such accidents (Slovic 2000, Renn 2008). The avoidance of such catastrophic fires is objective 10 below.

According to van Wee (2014) perceived safety is an important transport safety indicator as the ethically important aspect *freedom of movement* is at stake. Due to increased anxiety associated with driving in road tunnels, perceived safety (objective 11 below) may be particularly important for road tunnels (de Laval 2010, van Wee et al. 2014).

In 1997 the Swedish Parliament launched the design philosophy ‘*Vision Zero*’ for traffic safety which, as was described in the Theory Chapter, is much more that the goal to one day reach zero deaths and zero serious injuries on the road network including also road tunnels. Later other countries have followed or adopted similar visions (Elvik 1999). Vision Zero becomes objective 12 in the list of identified objectives below for road tunnel fire safety decision-makers (hereafter referred to as Objective 1 to 12):

(1) Limit the occurrence, generation and spread of fire and smoke.
(2) Means for safe self-evacuation.
(3) Means and safety for rescue operations.
(4) Load-bearing capacity of the construction.
(5) Organisational and administrative measures.
(6) Economic efficiency.
(7) Tunnel availability.
(8) The environment and long-term sustainability.
(9) Fair risk and benefit distribution.
(10) Catastrophic fires.
(11) Perceived safety.
(12) Vision Zero.

Quantitative and/or qualitative performance measures should be defined for each objective (without defining any safety limits). The derived objectives are argued to be important for road tunnel fire safety decisions but should not be seen as complete or mandatory. Each road (tunnel) planning and design process will highlight their relevant objectives. As the process is iterated objectives are modified to better capture the end qualities of the final tunnel design. The following steps (#3, #4, and #5) determine how these objectives are realised and prioritised when they conflict with each other. In particular they are evaluated in phase #4 where also performance measures are stated. In the next paragraph we enter the third phase of the decision-making process, generation of alternative solutions.

5.3.3 Alternatives

Alternatives are the different courses of action available to choose from. The decision can be no better than the best alternative, which highlights the need for creativity and innovation. At the same time, the number of possible alternatives is infinite, and knowledge and resources are limited which means that only a few good alternatives will be explored for each problem iteration. The alternatives should solve the problem framing and achieve the objectives set up. Vision Zero calls for inherently safer or fail-safe solutions to be created. For a particular decision, alternative solutions will depend on several local factors, e.g. whether the tunnel passes through a mountain, under water or below a city, how the user perceive the tunnel, and what type of construction is feasible. One important factor is whether a unidirectional or bidirectional tunnel is considered. To design a safe tunnel, it is important to begin considering safety at an early phase in the decision-making process. In such cases, inherently safer solutions are most likely to be realised (Rosmuller and Beroggi 2004).

Projects for tunnels that are under design do not start from zero. Previous projects, design guidelines, existing tunnels and legislation, set a standard that can be regarded as the first ‘status-quo’ alternative. For existing tunnels or tunnels under refurbishment the current tunnel solution becomes the natural status-quo alternative. In decision-making it is important that a status-quo alternative is defined since it offers a sound reference for all other alternatives (Hammond et al. 1999). The status-quo alternative evolves along the design process as more and more decisions are made about the design. Non-fire specific requirements can influence fire safety objectives, e.g. comfort ventilation to meet health limits on air quality can set tougher demands on the capacity of the ventilation system than smoke control in the event of fire. For example, if it is decided to start with a longitudinal ventilation system, such a system is added to the status-quo alternative. Once objectives have been assessed for the status-quo alternative, the two questions raised above in the problem framing phase are important for the generation of alternatives: 1) are there some objectives that alternatives score too low on or 2) is the status-quo alternative too good on some objective, i.e. perhaps too costly? Analysis and the generation of new alternatives will centre on the most critical objectives with regards to 1) and 2) above.

5.3.4 Consequence & uncertainty analysis

This section covers phase #4 of the general decision-making process where the consequences (each alternative would have) for each objective are analysed. It is structured according to the twelve objectives derived in phase #2.

5.3.4.1 Limit the occurrence, generation and spread of fire and smoke (Objective 1)

The aim of this objective is to offer protection against the origin, development, and spread of fire and smoke within the tunnel. The indicator most often used to express road safety is the number of fatalities per travelled vehicle km (van Wee et al. 2014). In this respect, road tunnels are safer than roads above ground, since the tunnel excludes pedestrians, cyclists and animals (Nussbaumer 2007, Malmtorp and Vedin 2014). This is also the measure most commonly used in risk analysis for road tunnels (sometimes also normalised per tunnel km) (PIARC 2008, PIARC 2012, Malmtorp et al. 2014). Such measures highlight the amount of vehicles and tunnel length, which also are identified as key measures for tunnel risk classification in the EC (2004) requirements. Although these factors cover the risk exposure, these two factors alone do not fully grasp road tunnel fire safety. From an Austrian survey of their road tunnel fires in 2006-2012 it is clear that the length of the tunnel and the number of vehicle kilometres are poor indicators of the amount of fires in different tunnels. Instead the survey highlights tunnels with long and steep approaches causing overheated heavy goods vehicles (HGV) engines or brakes (Rattei et al. 2014). Key factors identified for causing road tunnel fires are: tunnel inclination, tunnel curvature, the amount of HGVs, congestion, lighting conditions at tunnel portals and a gradient that goes from falling to rising (Martens and Jenssen 2012, Nævestad and Meyer 2014, Rattei et al. 2014), see Table 5. In a function-centred approach to road safety the aim is that the driver-vehicle-tunnel system remains in control (Hollnagel 2006). This concept highlights perceived safety, and organisational and cultural factors such as traffic management, proper vehicle maintenance and safe driving culture. These are important pro-active factors that commonly offer a better pay-off than more reactive measures (PIARC 2011).

Table 5 Performance indicators for the occurrence and severity of road tunnel fires.

Factors that increase the occurrence (likelihood) of tunnel fires	***Factors that increase the severity (consequences) of tunnel fires***
High tunnel inclination	Many HGVs (high fire load)
Poor design and lighting conditions at tunnel portals	Bidirectional tunnel
Abrupt change in tunnel gradient	Low ceiling height
High exposure (tunnel length and number of vehicles)	Fire spread to vehicles downstream
File changes	Poor means for self-evacuation
Many HGVs (multiple sources)	Small cross-section area

Due to the dynamics of tunnel fires, the smoke and heat initially rise to the ceiling and then follow the ventilation flow in the tunnel. This means that the fire separating function, to keep the fire in the tube of origin is relatively easily achieved (Ingason et al. 2015). More critical is the spread of fire within the same tunnel tube. For unidirectional tunnels the fire is not likely to spread as the vehicles downstream can be assumed to drive out of the tunnel. This case is further discussed in the following subsection. For bidirectional tunnels, the ventilation flow can increase radiation and heat towards vehicles downstream of the fire, making fire spread a key factor to control (Kim et al. 2010). The risk of fire spread is affected by the fire growth rate and the maximum heat release rate which increases with increasing ventilation in longitudinal ventilation flows until the cooling effect starts to dominate somewhere above 8 m/s (Li and Ingason 2011, Li et al. 2016). A key measure for the spread of fire is the ventilation conditions. A minimal amount of ventilation seems preferable for bidirectional tunnels with longitudinal ventilation to limit the generation and spread of fire. An alternative is a transversal ventilation system which can limit the fire spread to the smoke extraction zone (Ingason and Li 2011). Although often neglected, one of the most important parameters for fire spread is the tunnel ceiling height (Ingason et al. 2015). A low ceiling height results in faster fire development, higher temperatures and faster fire spread. An FFFS, e.g. sprinkler system, can control or supress the fire and eliminate the risk of fire spread (Mawhinney 2011). In Table 5 performance indicators that contribute to the occurrence and severity of tunnel fires are summarised. A key quantitative performance measure for the occurrence of fire is naturally the likelihood of fire. However, this must be supported by qualitative performance measures, e.g. from Table 5, since the likelihood of fire is difficult to model quantitatively as a function of relevant design parameters.

5.3.4.2 Means for safe self-evacuation (Objective 2)

The aim of this objective is to offer the users the means to reach a place of safety in the event of fire. Preferably this means that evacuees are not exposed to falling objects or physical obstructions, high temperature, high heat flux, high levels of toxic gases, or poor visibility. In tunnel fires, it is the smoke that causes fatalities. Life safety is therefore best achieved if evacuation through smoke can be avoided. A smoke free environment is achieved upstream of the fire in unidirectional tunnels with longitudinal ventilation along the traffic flow. Any vehicles downstream of the fire can drive out of the tunnel faster than the time it takes for the conditions in the smoke to become critical, see Figure 13. The deviating scenario would be one in which traffic downstream is impeded by a queue or by another accident, i.e. a double accident. This deviating scenario with a fire and stopped traffic downstream that is being engulfed by smoke has never occurred, which suggests that the probability is very low. Designing a unidirectional tunnel for the scenario of stopped vehicles downstream of the fire could make sense in a limit-based design approach but will receive less weight in a utility-based design approach. However, collisions and poor vigilance or safety distance to vehicles in front are among the most common causes for road tunnel accidents which highlights the case of collision with stationary traffic in a unidirectional tunnel. Traffic management becomes an important preventive measure to further limit the likelihood of such scenarios. For most, if not all, scenarios, the unidirectional road tunnel with a longitudinal ventilation flow along the traffic direction fail safely in the event of fire, see Figure 13 where no one is threatened by the smoke. Vehicles downstream the accident has exited the tunnel. Vehicles stopped upstream of the fire are safe from the smoke.

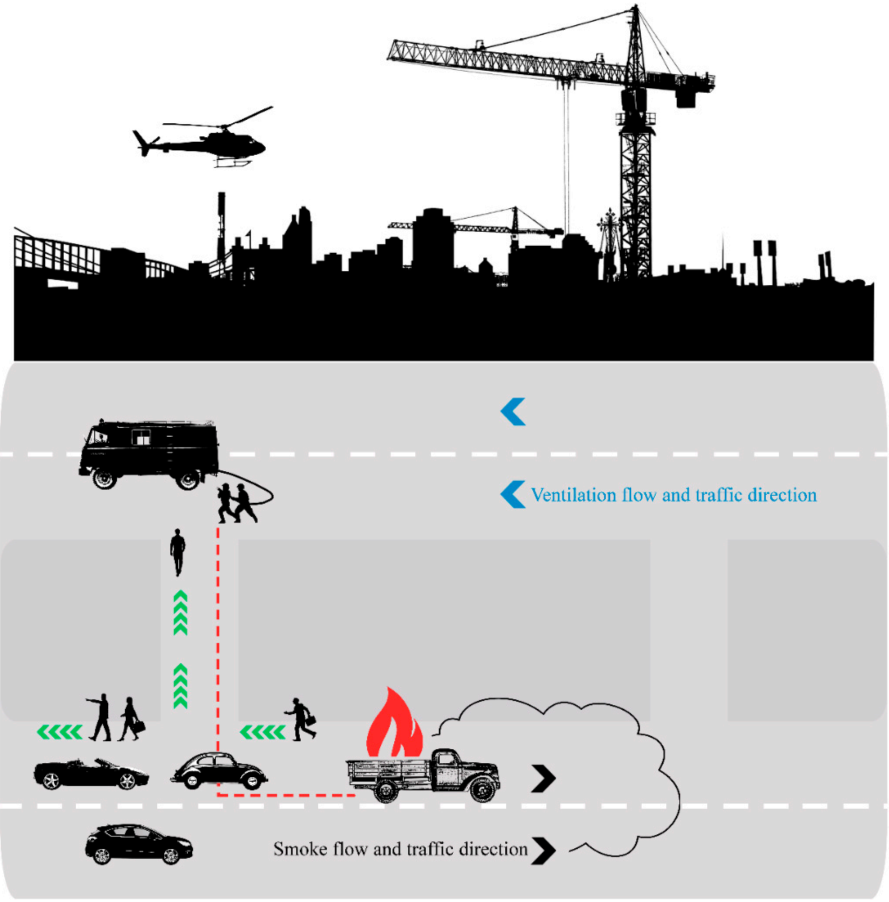

Figure 13 Fail-safe safety concept in a unidirectional road tunnel (Illustration: Mats Molid.).

For bidirectional tunnels, people can be expected to be found downstream and upstream of the fire, see Figure 14. In the Gudvanga road tunnel fire 2013, 67 people were trapped in the smoke downstream of the fire (AIBN 2015). As can be seen from previous large fires in bidirectional road tunnels, it is not a straight-forward task to evacuate a bidirectional tunnel in time to prevent deaths (Beard and Carvel 2012, Ingason et al. 2015). For longer tunnels a separate emergency pathway is required (EC 2004). The distance between emergency doors is likely not as important as convincing the tunnel users to leave their vehicles and quickly initiate their evacuation. For this reason a communication system that reaches inside vehicles is needed (Boer and Veldhuijzen van Zanten 2007). Again, the tunnel safety management needs to operate properly and expediently, with a clear message to exit the vehicles and to walk towards the closest emergency door. Once outside the vehicle, the tunnel user needs assistance from lights, sound, signs and tunnel design to walk towards an emergency door and to use it, potentially in dense smoke (Nilsson 2009, Nilsson et al. 2009). A properly trained organisation is needed to detect and deal with such events. The smoke and toxic gases concentration from a given fire depends on the tunnel cross-section and ventilation, the larger the ventilation and tunnel cross-section, the more the smoke is diluted with fresh air. However, if the ventilation is increased, the fire growth rate can increase and road users downstream are more quickly engulfed by the smoke. The benefit of a longitudinal ventilation system for evacuation in a bidirectional road tunnel is therefore less important than in unidirectional tunnel. The longitudinal ventilation system in bidirectional tunnels benefits mainly firefighting of a vehicle where the decision about flow direction or activation is taken by the local rescue service. A transversal ventilation system can improve the difficult situation, if it is designed and operated correctly (Ingason and Li 2011). When the transversal ventilation system works as intended, life safety risks only concern the tunnel users found in the smoke extraction zone. In the Tauern fire in 1999 the transversal ventilation system is reported to have worked well and reduced the death toll significantly (Beard and Carvel 2012). Despite this, four people were killed by the fire, three that stayed in their cars and one who suffocated 100 m from the fire from smoke inhalation (eight people were assumed to have perished in the initial crash) (Leitner 2001).

Figure 14 Fire failure state for bidirectional road tunnels (not fail-safe) (Illustration: Mats Molid.).

Despite the challenges cited above, the likelihood for road tunnel fire fatalities is low, e.g. Sweden and Norway have no reported fatalities from road tunnel fires (Nævestad and Meyer 2014, Malmtorp et al. 2016). This means that safety measures should not cost too much in a utilitarian approach where they are traded with Objective 6, cost effectiveness. An important quantitative performance measure is the number of expected fire fatalities. Uncertainties can be considerable which highlight the need for a sensitivity study. This measure should be complimented by qualitative performance measures that are poorly captured in the quantitative measure, e.g. the efficiency of different evacuation systems and actual human behaviour.

5.3.4.3 Means and safety for rescue operations (Objective 3)

The aim of this objective is that the rescue service can undertake lifesaving and fire extinguishing activities with satisfactory safety for their personnel. Again, unidirectional tunnels offer easy access to (and retreat from) the fire as the unexposed tube can be used for the rescue vehicles and the emergency door upstream of the fire for accessing the fire scene as in Fi. For bidirectional tunnels, rescue service vehicles are forced to use the tunnel portals of the tunnel directly involved in the fire to access the fire. The ventilation system must be operated in such a way that they can approach the fire from a smoke free direction. One lesson from previous fires is that the operation of the ventilation system and the rescuers needs to be coordinated, highlighting organisational aspects and the need for training. High-risk bidirectional tunnels with regards to fire occurrence, fire spread, and evacuation set the highest demands on the rescue service operation. For such tunnels the rescue service needs to arrive and to start the emergency operation quickly if they aim to extinguish an HGV fire and assist evacuees (Kim et al. 2010). However, in such cases they will need assistance from the ventilation system which probably will conflict with Objective 3, means for safe self-evacuation for road users downstream from the fire. It is then clear that extinguishing some bidirectional tunnel fires will not be possible. Instead the rescue leader may use all resources to assist evacuees, which is also a difficult mission on the downstream side of the fire. Such cases highlight the benefit from FFFS to control the fire at an early stage (Kim et al. 2010). The rescue service is often an active stakeholder in the design process which means that they are best suited to assess the performance of different design alternatives with regards to Objective 3.

5.3.4.4 Load-bearing capacity of the construction (Objective 4)

The aim of this objective is to ensure that the load-bearing capacity of the construction is adequate in the event of fire. This objective mainly concerns tunnels that are constructed in concrete. The inner ceiling or tunnel lining is reported to have collapsed or partly collapsed in large fires such as the St. Gotthard fire in 2001, but no tunnel is ever reported to have collapsed due to a fire (Beard and Carvel 2012, Ingason et al. 2015). One reason is that, for rock tunnels the load-bearing capacity is offered by the rock itself. Another reason could be conservative and limit-based requirements, as described below. After a large fire, surface lining and tunnel systems will be damaged and require tunnel closure and reparation, unless an FFFS is installed, see for example the Burnley fire in 2007 where the tunnel reopened after only 3 days (Beard and Carvel 2012). A tunnel collapse would likely require a longer closure as the tunnel would partly need to be rebuilt. Some types of concrete are prone to spalling from fire. This means that the load-bearing capacity quickly could become compromised. Spalling can be controlled by choosing concrete that does not spall, or by insulating the concrete from fire exposure.

Often a limit-based criterion is used as a design basis for the load-bearing capacity. Structural members are classified according to standardized fire exposures. A comparison of national road tunnel design guidelines identified fire exposures between 90 and 240 min (Kim et al. 2007). In a limit-based design approach the Runehamar T1 tunnel fire experiment where a HGV fire mock-up was set up that resulted in the highest HRR ever measured from a tunnel fire test, 200 MW, represents a worst case tunnel fire (Ingason et al. 2015). Comparing this fire with the standardized fire curves with regards to the exposure of concrete and reinforcement bars shows that 60 min represents a conservative exposure (Sjödin 2014). In order to achieve a longer fire, fire spread is necessary to occur to other vehicles downstream of the fire (Ingason et al. 2015). However, comparison with results from model scale experiments on fire spread to up to three targets indicates that 60 min still represents a conservative fire exposure (Sjödin 2014). Thus, it appears that the current limit-based approach to the load-bearing capacity is very conservative and a utility-based design approach has a good opportunity for making cost-effective trade-offs. A key performance measure is the probability of compromised load-bearing capacity.

5.3.4.5 Organisational and administrative measures (Objective 5)

The tunnel manager should ensure necessary organisational, administrative and technical measures for safe operation within system boundaries. These concerns include proper operation and maintenance and efficient traffic, incident and emergency management. For vulnerable tunnels, it should be ensured that the organisation that is created before, during and after the incident is fit to tackle the situation. Almost every system is dependent on maintenance and training to function in the intended way. This becomes more important as the number of systems and the size of the organisation becomes more complex. Organisational and administrative measures concern most phases of the safety work, from prevention, preparation and mitigation to intervention, after-care, evaluation and learning (PIARC 2007). Thus organisational and administrative measures are among the most effective safety measures albeit it may be difficult to quantitatively assess their utility (Reason 1997, PIARC 2007). Therefore, this objective deserves the highest priority and resource allocation must always be in proportion to other measures and requirements defined for safe operation and incident management. Scenario analysis and exercises have previously been identified as suitable methods to test the organisation (PIARC 2007, Gehandler et al. 2014). An indispensable complement is internal and external administrative control and a total quality management system (Reason 1997, Rasmussen and Svedung 2000). Performance measures for Objective 5 include the organisational resources a safety concept requires, how likely it will be matched and work in reality.

5.3.4.6 Economic efficiency (Objective 6)

It may be that inherently safer solutions can come at the same or even lower price than others, if safety is regarded early in the planning process (Rosmuller and Beroggi 2004). However, most safety measures come at a relatively high price and there is a long tradition within road traffic safety to evaluate the economic efficiency of safety measures by the use of cost-benefit analysis (CBA) (van Wee 2012, van Wee et al. 2014). This objective obviously favours a utility-based approach where the utility can be evaluated. The economic innovation is to conceptualize risk as a cost factor that can be exchanged (Renn 1998). The cost of a safety system can be evaluated against its benefit, e.g. by calculating the expected pay-back ratio during the system's lifetime. There are several ethical issues that a CBA ignores, e.g. fairness and perceived safety, as described in more detail below in 5.3.4.9 and 5.3.4.11, that may need to be considered in addition (van Wee 2012).

5.3.4.7 Tunnel availability (Objective 7)

A high availability with regards to tunnel vehicle capacity (mobility) will sometimes conflict with safety, e.g. authorities trying to reduce speed limits against the will of local communities that value mobility higher than safety. At other times mobility is in favour of safety, e.g. the installation of FFFS causes a shorter tunnel downtime after fire (Dix 2012), although the reduced tunnel mobility, e.g. caused by FFFS false alarms and maintenance, needs to be considered as well. Another key parameter for the tunnel mobility is the number of road lanes. Mobility can be included in the CBA.

Availability with regard to usability for all road users can be at stake as only motorized road users commonly are allowed in road tunnels (related to fairness), and due to fear of using road tunnels (related to perceived safety). The tunnel can increase the usability of land above ground, e.g. if a highway through a city is turned into a tunnel covered with a park. Another aspect related to safety is whether safety systems are valid for all road users, e.g. including those with mobility restrictions.

5.3.4.8 The environment and long-term sustainability (Objective 8)

The Swedish Environmental Code aims to ensure a sustainable (ecological, social, cultural and socioeconomic) development for current and future generations. Human health, biodiversity, valuable natural or cultural environments should be considered such that the overall damage is minimized. The MKB process highlights many concerns that can conflict with fire safety objectives. Safety systems have an environmental impact from the cradle to the grave, but they can also favour environmental concerns, e.g. through reducing the amount of vehicle fires and tunnel damage. Vehicle fires contaminate air, water and soil. Afterwards there is an environmental impact associated with vehicle replacement and tunnel restoration. This could be included in a CBA or fire-LCA (Andersson et al. 2007). Apart from the construction of transport systems and general vehicle emissions, which are a greater question than road tunnel fire safety, this objective mainly concerns the construction of the tunnel and its fire safety measures, e.g. whether a ventilation shaft is to be situated in the habitat of an endangered species (Gehandler et al. 2012b), or the carbon footprint from safety measures, which can be estimated using LCA.

5.3.4.9 Fair risk and benefit distribution (Objective 9)

Rule based ethics, e.g. Kant (1724-1804) and Rawls (Hermansson 2010), emphasize that people should be used as ends in themselves, not merely as means. Such ethical theories highlight winners and losers. Unfortunately, decision-making for transport system fire safety is difficult to do without having losers. Nevertheless, who the winners and losers are is an important factor that should be included in any evaluation (van Wee 2012). In general the motorized road users benefit most from road systems, and other groups in society, e.g. children and young, benefit less, but share a higher risk (Hokstad and Vatn 2008). According to Rawls' second principle, economic and social inequalities are only justified if they benefit all of society and in particular the least advantaged members (Ersdal and Aven 2008). Children and young are exposed to higher risks and reap fewer benefits from roads since they are more often pedestrians or cyclists. Non-motorized road users are in general not allowed in road tunnels. Although a city tunnel can bring benefits to non-motorized road users above ground compared to a situation without the tunnel, it is the motorized road tunnel user who benefits from improved road tunnel safety. On the other hand, if the perceived safety of the road tunnel is high, more motorists will use it, which will benefit non-motorized users above ground.

5.3.4.10 Catastrophic fires (Objective 10)

What makes road tunnel fires *catastrophic*? The weight placed on this objective depends on the perceived fear associated with road tunnel fires and the severity of catastrophic fires, relative to other hazards that our society faces today (assuming that we have a limited amount of resources to spend on safety). The catastrophic potential that a risky activity has is mainly related to the following factors (Slovic 1987, Slovic 2000, Renn 2008):

- Reversibility: whether the situation can be restored to the state before the damage occurred, e.g. reforestation.
- Persistency with regards to the temporal extension of potential damage, e.g. persistent chemicals.
- Dread towards the activity in question, e.g. nuclear power plants.
- Extent of direct damage with regard to fatalities, injuries and socioeconomic losses, e.g. explosion causing hundreds of fatalities.

Fortunately, road tunnels score low on all these factors compared to other technological risks such as nuclear power plants, genetic engineering or chemical industries. There are no reported cases when a tunnel could not be restored to its state before the fire accident. Although persistent chemicals could be released in fires, it is argued that the contributions from road tunnel fires are insignificant. The dread towards auto accidents and fires in general is neutral or low (Slovic 1987). A Swedish survey found no difference in risk perception between fire and road traffic accidents (Carlsson et al. 2008). This suggests that the dread towards road tunnel fires is neutral or low as well since it is a subset of auto accidents and fires. Autonomy is an important moral value, and driving a car through a tunnel is a risky activity that many people choose to do (Roeser 2006). However, it is also true that about one in three of all drivers are anxious and 4 % even avoid driving through road tunnels, but it is plausible that this subset still would feel more dread towards, other risks, so that in comparison, road tunnel fires score low on dread. Increasing the perceived safety can increase the well-being of anxious road users (de Laval 2010, van Wee et al. 2014).

In Table 6 the three most severe road tunnel fires in Europe are summarised (Leitner 2001, Beard and Carvel 2012, Ingason et al. 2015). Road tunnel fires have limited direct damage compared to accidents causing hundreds of victims and considerable material damage such as the petrochemical explosions in Texas city killing over 500 or the collapse of the great Teton dam destroying 100 000 acres of farmland (Perrow 1999). Apart from fatalities and injuries, direct consequences can also be expressed in terms of property loss, socio-economic effects resulting from tunnel closure or secondary effects resulting from a tunnel collapse, e.g. for tunnels with buildings on top or submerged water tunnels. In several large road tunnel fires the structure was damaged, requiring a few weeks or months for reparation during which time the tunnel remained closed. There is no report of a tunnel fire where the load-bearing capacity of the construction failed (Beard and Carvel 2012, Ingason et al. 2015). To summarize, the catastrophic potential of road tunnels is low or very low compared with other risks that our society faces.

Table 6 The three most severe road tunnel fires in Europe.

Year and Tunnel	***Tunnel length (m)***	***Bi/uni-directional***	***Cause of fire***	***Consequences***	
				Life Safety	***Property / Socio-economic***
2001, St. Gotthard, Switzerland	16920	Bi (parallel service tunnel)	Head-on collision between two HGVs	11 dead	Severe damage to 230 m. Closed for 2 months
1999, Tauern, Austria	6765	Bi	An HGV collided with stationary traffic killing 8 in the crash.	12 dead (8 from the initial crash)	Severe Damage to 450 m. Closed for 3 months
1999, Mont Blanc, France-Italy	11600	Bi	HGV. Plausible diesel leakage on hot surface	39 dead	Severe damage to 900 m. Closed for 3 years

5.3.4.11 Perceived safety (Objective 11)

Compared with roads above ground, a Swedish survey found that about one in three people are, at least sometimes, anxious when driving in tunnels and 4% avoid driving in tunnels (de Laval 2010). A Norwegian survey found that one in five feel anxious in tunnels and 4% are very negative to tunnels (Flø and Jenssen 2007). According to Rawls' first principle of justice, everyone has equal basic rights and freedoms, e.g. freedom of movement, that can never be violated (van Wee 2012). A high perceived safety level will reduce stress and consequently increase the freedom of movement, which are ethically important factors (van Wee et al. 2014). By studying the perceived safety, the feeling of being in control and alert can be increased, which will reduce accidents and thereby increase safety (Flø and Jenssen 2007, de Laval 2010). This concept highlights a problem-driven approach where the joint driver-vehicle-tunnel system should remain in control (Hollnagel 2006), and is also in accordance with central ideas of Vision Zero. The perceived safety can be measured quantitatively and qualitatively with computer driving simulations and from operational driving experiences (Flø and Jenssen 2007, de Laval 2010). A CBA-based design approach is not well suited to account for perceived safety (van Wee 2012).

5.3.4.12 Vision Zero (Objective 12)

Objectives 1-5 and 11 prescribe what is required to reach Vision Zero for road tunnel fire safety. Road tunnel fire risk mainly depends on whether the tunnel is uni- or bidirectional, and on factors that affect the likelihood and consequences of fires. Many unidirectional road tunnels with longitudinal ventilation along the traffic flow fail safely in the event of fire in the sense that the spread of fire is limited, and the spread of smoke does not affect road users, which means that a safe self-evacuation is ensured. The rescue service can safely access the fire from the upstream side. Organisational and administrative measures need to ensure that the tunnel is operating within safety constraints. Perceived safety helps to eliminate errors and makes the tunnel inherently safer. Sustainability will in most cases not conflict with fail-safe solutions but will instead be mutually supportive. It appears that unidirectional road tunnels can be managed to comply with the philosophy of Vision Zero.

On the other hand, many bidirectional road tunnels do not fail safely in the event of fire. For bidirectional road tunnels the main difference is that vehicles and road users are found on both sides of the fire. This means that there is no safe side to push the smoke, which increases the risk for fire spread to vehicles and requires consideration of evacuation through smoke. The smoke from tunnel fires can lead to loss of life or serious injuries, which means that more effort in #3, generation of creative alternatives, is required to reach Vision Zero.

5.3.4.13 Summary

In Table 7 all objectives, their analysis and performance measure are summarised. In the next section we enter the last phase of the general decision-making process.

5.3.5 Evaluation & trade-off

The purpose of evaluation is to identify the solution that best solves the problem, i.e. best achieves the objectives. As the decision-making process is iterated through #1-#5, the problem is being reframed to reflect the stakeholders' key values and objectives. The basic idea in decision-making is that the best solution is the one with the highest aggregated utility for *all* problem objectives. As the problem is iterated, key objectives are identified, and it is ideally these that should drive the problem solving so that any tools are adapted to the problem and not the other way around. Decision-making theory helps to eliminate objectives and alternatives to a manageable decision. As an example, objectives for which all alternatives are similar and alternatives that are inferior on all objectives can be eliminated.

Table 7 Methods used for analysis and performance measures of each obejctive.

Objective	**Analysis**	**Performance measure**
1. Limit the occurrence, generation and spread of fire and smoke	Standard/testing of compartmentation or wall lining material. Fire spread or fire development, CBA	Fire rating and cost-benefit
2. Means for safe self-evacuation	Design standards, risk analysis, and CBA	Compliance with standards, risk, and cost-benefit
3. Means and safety for rescue operations	Experience, scenario & emergency exercises, risk analysis, and CBA	Fire fighter perception, risks to fire fighters, cost-benefit
4 Load-bearing capacity of the construction	Testing or inquiry, risk analysis, and CBA	Fire rating, risk, cost-benefit
5. Organisational and administrative measures	Internal and external administrative controls, planning, training, scenario and emergency exercises, quality system.	Expected level of performance, perceived handling of different of scenarios.
6. Economic efficiency	CBA	Cost-benefit
7. Tunnel availability	Expected availability, CBA	Number of vehicles, cost-benefit
8. The environment and long-term sustainability	MKB-process, LCA, Environmental Risk Assessment	The environmental impact, e.g. CO_2-equivalents, impact on surrounding species.
9. Fair risk and benefit distribution	Risk analysis, ethical/social analysis	Distribution of risks and benefits for different groups or individuals
10. Catastrophic fires	Risk analysis, CBA	Likelihood for catastrophic fires, cost-benefit
11. Perceived safety	Driving simulation/experience	Perceived driving experience; control/stress
12. Vision Zero	Inherent safer/fail-safe design	Safety concept and boundaries

5.3.5.1 Key objectives

Among the 12 identified objectives, more or less important objectives can be identified, which may vary between projects. Safety is a dynamic concept that is dependent on past and present management. Sound organisational and administrative measures are a prerequisite for the safety functions of the system (Weick 1987, Reason 1997, PIARC 2007). Perceived safety has a positive impact on both safety and ethics, unlike most ordinary safety measures (Objectives 1-4). Perceived safety is further aimed at prevention, which is more effective than cure, e.g. Objectives 2-4. Qualitative aspects such as perceived safety and organisational and administrative measures are central strategies within the Vision Zero safety concept for tunnels.

It is argued that catastrophic road tunnel fire risk is *de minimis*. The catastrophic potential is low compared to other risks that modern societies face, and the likelihood of occurrence is very low for most road tunnels, not least unidirectional. Issues of fairness (Objective 9) are relevant for road tunnels and can affect the desired level of safety or which types of safety systems are installed.

Tunnel fire safety is an issue for today's generation while many environmental issues, e.g. the protection of endangered species, may have consequences for current and future generations. Naturally this increases the weight put on long-term sustainability issues.

Vision Zero (Objective 12) requires that fatalities and serious injuries are eliminated for all (usability) but that mobility (Objective 7) follows from safety. Environmental issues, Objective 8, should be mutually supportive. Vision Zero does not allow for safety to be traded away, as could happen in CBA, for example. Only if two measures offer the same level of safety can CBA be used to choose between them (Tingvall 1997). Although mobility and cost are downplayed in Vision Zero, inherently safer or fail-safe solutions are not necessarily worse than other solutions, in the long run they may very well pay off (Rosmuller and Beroggi 2004, Whitelegg and Haq 2006). Given that society actually wants improved road safety, which is strongly supported from a political standpoint (Whitelegg and Haq 2006), then Vision Zero emerges as the best starting point.

5.3.5.2 Aiming for Vision Zero

As could be seen in the previous sections most unidirectional road tunnels with longitudinal ventilation along the traffic flow can be engineered to fail safely in the event of fire. The Vision Zero philosophy includes the key objectives identified above. Among compliant alternatives, trade-offs can be struck regarding e.g. cost and mobility.

If the initial alternatives do not achieve Vision Zero, e.g. do not fail safely in the event of fire, much effort and creativity should be invested in phase #3 to develop inherently safer or fail-safe alternatives, or intolerable events must be eliminated. For the system to fail safely, safety systems need to be able to ensure tolerable conditions without intervention. As was seen in section #4, bidirectional road tunnels are problematic in this respect. A design option could be to convert the tunnel into a unidirectional tunnel separated by a wall or to build a second tube so that a unidirectional road tunnel is achieved. However, an analysis must check the feasibility and cost. Intolerable events can be eliminated if HGVs are prohibited from the tunnel, since they provide the fire load giving rise to intolerable conditions. However, this may not be publicly acceptable. If, despite effort, a fail-safe alternative cannot be achieved the best trade-off is sought.

5.3.5.3 Trade-off

Given that objectives of higher priority cannot be reached or are equally considered for all candidate alternatives, trade-offs can be struck with a utilitarian approach (Elvik 2001). This will highlight a set of quantitative performance-measures that are sensitive to the different design alternatives (objectives for which all alternatives have the same score can be removed for this iteration). In a CBA the expected utility is estimated with respect to safety (Objectives 1,2 & 4), cost (Objective 6) and mobility (part of Objective 7). This should also be supported by qualitative performance measures which are not captured in the CBA. For example, regarding who benefits or is at risk (Objective 9), environmental aspects (Objective 8), organisational aspects (Objective 5) and perceived safety (Objective 11), i.e. closer to a Multi-Criteria Analysis (MCA) than a CBA. The decision-maker should next weigh each attribute with regards to its relative importance, i.e. the subjective utility. The alternative with the highest aggregated subjective utility is then the best alternative.

The risk evaluation and consequently the problem iteration finishes when the client and the design group feel that the design problem has been solved. The solution then either arguably meets identified objectives (qualitative and quantitative performance measures), or it is argued to be the "best" trade-off between conflicting objectives. The proof is all documentation through each decision stage and iteration. Therefore, someone from the outside can see the evolvement of problem framing, objectives, alternatives, analysis, and evaluations as a justification of the chosen design.

6 Discussion

The thesis contains four papers (Paper I-IV) and four research objectives (RO1-4). In the introduction, this thesis work was described as a journey to explore the question of how safe is safe enough. This journey started with a limit-based design approach. Then, safety is treated by limits, e.g. a design fire and criteria for acceptance or a risk criterion on the number of fatalities that can be tolerated. Safety is seen as absolute; it cannot be traded with other objectives. In the ethos of this approach a design guide was developed (ROI and Paper II). The design guide defines performance-based requirements and propose one way to verify that they are met. In large it is a compromise between existing legislation, best practice and latest tunnel fire research.

A key method for road tunnel fire safety design is risk analysis. Paper III (RO2) investigated how accurate tunnel fire dynamic models used in risk analysis are compared to experimental data. It is argued that the error from using the proposed equations in risk analysis is comparatively small. Although the comparison was made on limit-based risk analysis models, the equations are equally applicable (with the same error) in probabilistic risk analysis.

The journey continued to investigate the utility-based design approach where sufficient safety is achieved when the utility is maximized. In this development, safety is allowed to be a relative concept depending also on other objectives. The utility-based design approach is most often based on CBA. Since some important factors such as perceived safety and fairness are poorly treated in CBA, a more general decision-problem framing was investigated. It was further found that Vision Zero highlights some important qualities such as inherent safety or fail-safe solutions which are not highlighted in limit-based design or the CBA framework. Paper I & IV visualize different ways to frame the fire safety problem (RO4) and argues for that the whole decision process should be acknowledged. Consequently, a new design framework for fire safety design was proposed (RO3 and Paper IV). The new design framework in Paper IV does not invalidate or replace previous work, e.g. in Paper II and Paper III. Rather it is compatible with, for example, performance-based safety objectives (can be identified from Paper II) and risk analysis modelling (see Paper III for model choice and risk analysis uncertainties).

The key method in Paper I is a literature review study. Paper III is based on an empirical comparison between experimentally measured data and modelled output.

This is, from a theoretical point-of-view standard scientific work that tries to understand certain aspects of reality, i.e. how things *are*. Paper II & IV are concerned with design frameworks and belong to what is called design problems. Design problems are concerned with how things *ought* to be. The theoretical framework of a design problem specifies the *oughts'* that matters. Unfortunately, there is no neutral option. This is really a democratic and political issue, open for discussion. How should we best use our societal resources? What matters? The method of Paper II can be described as a best practice approach from an engineering point-of-view. Then, how safe the tunnel should be, becomes a technical question in terms of specifying safety limits. In the work behind Paper II such limits were proposed without much consideration of the democratic and political issues. In contrast, Paper IV illustrate how more democratic factors can be included in the design decision. The method of Paper IV is much more about finding a process that allows for inclusive decision-making, and about identifying factors that matters. In Paper IV no safety limits are proposed; that is the outcome of each actual decision. Since Paper II and IV deal with design problems, they cannot be verified to be right or wrong. We can learn from application and argue for or against them, but there will never be a definite answer. Indeed, a fire safety problem can be framed in different ways, which also affect how the decision in the end is justified. Between the limit-based design approach and the decision-oriented approach suggested in this thesis, it is noted that safety decisions are justified in very different ways. In the limit-based design approach safety levels are defined early in projects. In the end, the final decision is justified by the assessment of whether the selected solution achieves the safety limits set up. In the decision-oriented approach objectives and measures are defined, but without the exact limits as to what would constitute a safe (and unsafe) solution. Instead, considering all objectives and all learning along the process, the safety level emerges from the chosen design, justified by its overall superior utility to the decision-maker, including qualitative factors. The crux of the matter is whether the safety decision should be made with more information (the decision-oriented approach; all objectives and the solutions explored along the way) or less (the limit-based approach; each safety objective treated in isolation and safety objectives defined early).

Whether or not we will see a move in FSE or road tunnel fire safety design towards the proposed design framework with a more open problem-framing to find the best solution, only the future can tell. One trend, I believe, is the use of ALARP criterion. This may be a first step to make safety more relative to other objectives (in this case mainly cost). Sweden and the EC requirements for road tunnels within the EU lack such a criterion but ALARP criteria are, for example, found in Italy and Switzerland (PIARC 2012). Sweden does not yet have an ALARP criterion although it is starting to be used in projects. If the ALARP area is very wide, it becomes a utility-based design approach. The trend to move towards a decision-oriented approach to fire safety problems is weaker but recent examples can be found in the literature. Akaa et al. (2017) takes a decision-oriented approach that, together with stakeholders, finds a balance between several objectives for the protection of steel structures. Bilson (2018) finds a trade-off between existing standards and other objectives in negotiation with the tunnel owner for a rail system ventilation rehabilitation. This was possible since existing regulation only applies to new tunnels, the regulation was used more as a design guide.

6.1 The proposed design framework: objections and implications

In practice, the proposed framework is expected to result in better road tunnel fire safety decisions, taking a larger set of objectives, e.g. environmental, ethical and economic, into consideration, although, it may be perceived otherwise. A cultural perspective on risk reveals that different groups in society prefer different risk management approaches (Renn 1998). Some groups in society, e.g. 'egalitarians', would appreciate the more open and transparent decision process where their input is valued and needed along the whole process. Therefore, the proposed process would probably be perceived to be less paternalistic and elitist. On the other hand, some groups in society would prefer a more rigid process based on more prescriptive rules and procedures with more certain outcome, e.g. this is the typical sphere of bureaucrats. For bureaucrats the proposed process would probably be perceived to lack legal certainty, and perhaps in some sense be seen as 'dopey'.

Of course, someone in favour of limit-based design would have some objections to the proposed design framework. The most obvious clash is the idea to see safety as a relative concept. An example of safety as something absolute comes from Malmtorp et al. (2016) who argues that safety should be equal in all Swedish tunnels whether they are road, rail or metro. However, unfortunately, safety will never be the same for all people at all times and place. This does not seem to be something that we in general would even like. Economic and risk perception studies (e.g. Slovic 1987, Sjöberg and Ogander 1994) reveal that the amount we are willing to pay to save a life heavily depends on the situation, e.g. depending on whether it is children or extreme athletes who are exposed. Thus, we do not want risks to be the same in all situations. I would argue that it is natural to find variations in society and that it should not be our objective to make everything equal. Instead this highlights the constructivist and relative side of how we prioritize risk decisions. Naturally we can do this within fire safety as well as in society at large. I think this highlights the core controversy between two different views of safety and problem framings; Is safety some absolute right with natural levels that must not be violated, or should it be a decision objective among others (i.e. relative)? I think there is much evidence for the later, that safety is one of several decision objectives and therefore must be allowed to vary with these. The Swedish Environmental Code, which is the most fundamental law for road design, does not regard safety to be more important than other aspects that are considered. Further, the Swedish Civil Contingencies Agency, acknowledge that other factors must be balanced against increased societal safety (MSB 2014).

At first glance it may seem that the proposed design process would require more resources since more objectives are included in the analysis. However, a central aspect in iterative decision-making is to analyse the parameters that matter at the level of detail required to solve the objectives set up. As an example, Bjelland & Aven (2013) describe how a lot of resources were directed into finding a reference tunnel that would never to be built. One reason is the limit-based idea that the tunnel should be equally safe as a reference tunnel. In the proposed design framework, the focus would be on the actual tunnel design and the decision problem that needs to be solved and engineered. In this way it could be argued that resources are spent where they matter, to find the best solution given our objectives and resources, and that we could make better decisions.

The proposed design framework primarily challenges the STA and fire safety engineers to stop thinking about safety in limit-based terms. Existing guidance and best practices still apply, and fire safety objectives should still be defined. But engineers should be careful about defining limits on “acceptable” safety. Instead they should focus on finding creative solutions that best fulfil *all* objectives. In the end the decision-making process should find the right balance and trade-offs between all objectives, . A challenge with the proposed design framework is that a dialogue with different stakeholders is required throughout the planning and design process. For some stakeholders, e.g. the rescue service, this is already the case. But other stakeholders, e.g. The County Administrative Board are more involved early in the project. However, through consultation meetings, which are already arranged throughout the project, safety decisions can be discussed and followed up with stakeholders along the whole planning and design process, which is the ambition of the proposed design framework.

7 Conclusions

The research objectives for this thesis are restated below for convenience:

RO1	Develop a performance-based design guide for road tunnel fire safety in a Swedish context.
RO2	Investigate the accuracy and applicability of tunnel fire dynamic models for road tunnel fire risk analysis.
RO3	Propose a fire safety design framework that address identified challenges.
RO4	Illustrate different fire safety problem framings.

Conclusions with reference to the research objectives are as follows.

To address RO1, a guideline with performance-based requirements and an approach for assessment of fire safety in road tunnels, in accordance with existing regulation and best fire safety praxis, was developed.

Secondly, it was demonstrated that a simple model based on tunnel fire dynamics theory for the calculation of time to compromised tenability is a viable option for road tunnel risk analysis (to address RO2). The accuracy in predicting the time to compromised tenability is argued to be sufficient for tunnel risk analysis with longitudinal ventilation above 1 m/s.

Thirdly, a fire safety design framework has been proposed (to address RO3). The design framework acknowledges the scientific or technical aspects of risk and social structures, together with the ethical and democratic aspects of risk. It is based on a general decision-making process where the problem and its solutions can be reframed and negotiated with stakeholders along an iterative and creative process. It is argued that a Vision Zero design philosophy with its emphasis on inherently safer or fail-safe systems offers the best safety prospect. Only the whole decision process can ensure that the best solution is found.

In the proposed design framework, safety is relative, i.e. one decision objective among others, congruent with general decision-making ideas. The safety problem is reframed from the limit-based framing in which safety levels are defined early in the project and later verified into a problem-solving framework aimed at finding the best solution, all aspects considered. I hope this thesis, together with other critical work (Lundin 2005, Babrauskas et al. 2010, Bjelland 2013), will initiate discussions to foster the development of greater benefit from fire safety engineering in a performance-based regime and a quickly changing world.

Fourthly, to address RO4, this work has visualized different fire safety problem framings. In particular three framings have been discussed; 1) *How safe the tunnel should be* implies a limit-based safety level framing, 2) *enough safety in relation to cost* implies a CBA-based framing, and #3 *enough safety is offered by the option that best fulfils stakeholders decision objectives* implies a more open decision-oriented framing where different types of factors can be included in the decision process.

8 Future research

The journey of road tunnel fire safety design does not stop here. Paper IV offers an alternative design framework for fire safety design. A key issue concerns the nature of design problems in general. A design framework can only be evaluated based on the experience of how well many different design problems are being solved. The proposed framework should be applied, evaluated and improved. Further, I am convinced that social science, philosophy and ethics have much to contribute to the theoretical framework of fire safety engineering. Not least decision-making and ethics are needed to better mirror the societal demand for fire safety. Since risk largely is managed at meetings, not only risk analysis is used, but also risk in a broader sense that also includes values and feelings. Such values are, according to Finucane (Finucane 2005), best described using narratives or stories, which most likely is what actually happens during the work meetings or decision meetings where risk is managed. An example could be how long-term sustainability issues are communicated through narratives. Further studies are needed to balance the current positivistic and limit-based design approach:

- Apply the design framework to real problems and improve it based on the experience of how well the design problem is being solved,
- Explore how risk is communicated at internal meetings aimed at risk management and possibly improve the communication by adding missing parts, e.g. feelings or values.
- Study how different objectives in road tunnel fire safety decisions can best be weighed against each other (those that CBA does not deal with satisfactorily),
- Develop an efficient Vision Zero *for fire safety* with efficient concepts and strategies towards inherently safer or fail-safe designs,
- Explore how creativity and innovations can be encouraged in fire safety design processes, and
- Explore how the decision-making process can become the proof of quality and legal appliance.

Another interesting field of research would be to build on the insightful ideas of Weick (1976), Weick (1987), both related to safety as a dynamic non-event and to the idea of loosely coupled systems as opposed to dense or tight coupling which most often seems to be assumed in e.g. technical risk analysis. This could be a very good complement to QRA since it directs interest and investigation to blind spots of most QRA: the vast majority of cases that work as intended (i.e. safety!) and to loosely coupled systems that most likely either are disregarded or overly simplified in the QRA. The idea of loosely coupled entities could increase the understanding of any system since our language becomes richer in describing it. Fire safety engineering and human behaviour is probably a good area to start with since, for example, human behaviour in mathematical language hides more of reality than it can possibly explain. The idea of loose coupling could also provide tools for working with discrepancies between how things *should* work and how they *actually* work.

The point of ignition is an important parameter for the fire development in tunnels with mechanical ventilation and consequently any risk analysis that is performed. Yet this parameter has not been investigated in tunnel fire dynamics and never seems to be discussed in road tunnel risk analysis. Basic research is required to explore the fire development for different ignition positions on the object in question. A hypothesis is that the fire growth rate of a vehicle inside a tunnel would decrease as follows depending on where on the object the fire starts: ignition in the middle > ignition at the upstream side > ignition at the downstream side. Such theory could, for example, be exploited in risk analysis for unidirectional road tunnels with ventilation along the traffic flow. Ignition in the front of vehicles, e.g. the engine compartment, will then have a slower fire development.

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